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APPLICATIONS OF MULTICONDUCTOR TRANSMISSION LINE THEORY TO THE PREDICTION OF CABLE COUPLING

Digital Computer Programs for the Analysis of Multiconductor Transmission Lines

University of Kentucky

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Four digital computer programs, XTALK, XTALK2, FLATPAK, FLATPAK2, for determining the electromagnetic coupling within an (n+1) conductor, uniform transmission line are presented. Sinusoidal steady state behavior of the line as well as the TEM or "quasi-TEM" mode of propagation are assumed.

XTALK and XTALK2 consider lines consisting of n wires (cylindrical conductors) and a reference conductor. The surrounding medium is homogeneous and lossless.

(Con'd)

XTALK assumes that all (n+1) conductors are perfect conductors whereas XTALK2 considers the conductors to be lossy. There are three choices for the reference conductor: a wire, a ground plane, an overall cylindrical shield.

FLATPAK and FLATPAK2 consider (n+1) wire ribbon (flatpack) cables in which all wires are identical and are coated with cylindrical, dielectric insulations of identical thicknesses. All wires lie in a horizontal plane and all adjacent wires are separated by identical distances. FLATPAK considers the wires to be perfect conductors and FLATPAK2 considers the wires to be lossy. The dielectric insulations are considered to be lossless.

General termination networks are provided for at the ends of the line and the programs compute the voltages (with respect to the reference conductor) at the terminals of these termination networks for sinusoidal steady state excitation of the line.

PREFACE

This effort was conducted by The University of Kentucky under the sponsorship of the Rome Air Development Center Post-Doctoral Progarm for RADC's Compatibility Branch. Mr. Jim Brodock of RADC was the task project engineer and provided overall technical direction and guidance.

The RADC Post-Doctoral Program is a cooperative venture between RADC and some sixty-five universities eligible to participate in the program. Syracuse University (Department of Electrical Engineering), Purdue University (School of Electrical Engineering), Georgia Institute of Technology (School of Electrical Engineering), and State University of New York at Buffalo (Department of Electrical Engineering) act as prime contractor schools with other schools participating via sub-contracts with the prime shcools. The U.S. Air Force Academy (Department of Electrical Engineering), Air Force Institute of Technology (Department of Electrical Engineering), and the Naval Post Graduate School (Department of Electrical Engineering) also participate in the program.

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Command (ADC), Hq USAF, Defense Communications Agency (DCA), Navy, Army, Aerospace Medical Division (AMD), and Federal Aviation Administration (FAA).

Further information about the RADC Post-Doctoral Program can be obtained from Mr. Jacob Scherer, RADC/RBC, Griffiss AFB, NY, 13441, telephone Autovon 587-2543, commercial (315) 330-2543.

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I. INTRODUCTION

This report is the seventh in a seven volume series documenting the Application of Multiconductor Transmission Line Theory to the Prediction of Cable Coupling. The purpose of this report is to implement the analytical techniques described in Volume I of this series [1] in the form of digital computer programs.

Crosstalk or electromagnetic coupling between wires (cylindrical conductors) in densely packed cable bundles can be a serious contributor to the degradation in performance of modern electronic systems. A recently developed digital computer program, IEMCAP, provides a general analysis capability for determining overall electromagnetic compatibility of aircraft, ground and spacecraft systems [3]. The computer programs described in this report are intended to provide a supplement to the analysis capabilities of IEMCAP by providing a more fine-grained analysis of wire-coupled interference.

IEMCAP is intended to be used to model all recognizable coupling paths on aircraft, ground and spacecraft systems. By virtue of the large size and complexity of many of these systems, detailed modeling of the coupling paths is not feasible in a program such as IEMCAP. To avoid excessive computer run times, the models of the various coupling paths used in IEMCAP are generally quite simple and represent bounds on the coupling. Consequently, the predictions of IEMCAP are generally somewhat conservative. However, once a potential wire-coupled interference problem is pinpointed by IEMCAP, the computer programs described in this report can, in many cases, be used to determine if an actual interference situation exists and the precise level of the interference.

Four programs are described: XTALK, XTALK2, FLATPAK, and FLATPAK2.

XTALK analyzes three configurations of transmission lines: (1) (n+1) bare wires, (2) n bare wires above an infinite ground plane, and (3) n wires within a cylindrical shield which is filled with a homogeneous dielectric. All conductors are considered to be perfect conductors. XTALK2 analyzes the same three structural configurations as XTALK except that the conductors are considered to be imperfect conductors. FLATPAK analyzes (n+1) wire ribbon cables. All wires are assumed to be perfect conductors. FLATPAK2 analyzes the same configuration as FLATPAK except that the wires are considered to be imperfect conductors. In all of the above programs, the medium (media) surrounding the conductors is assumed to be lossless. Sinusoidal, steady-state excitation of the line is considered, i.e., the transient solution is not directly obtained. Comparison of predicted to experimental results are obtained using these programs in Volume III and Volume IV of this series [4,5].

All programs are written in FORTRAN IV Language and are double precision. Changes in the programs to convert them to single precision arithmetic will be indicated. All programs have been implemented on an IBM 370/165 computer at The University of Kentucky using the Fortran IV, G level compiler and should be easily implemented on other computers.

It is, of course, difficult if not impossible to write a general computer program which will address all types of transmission line structures which the user may wish to investigate. The four programs included in this report form an initial library of analysis capabilities for wire-coupled interference problems. Other programs which address more specific structures and structures not considered by these four programs will be documented in other volumes of this series as well as in future RADC publications as they are developed.

II. FORMULATION OF THE MULTICONDUCTOR TRANSMISSION LINE (MTL) EQUATIONS

In this chapter, the distributed parameter, multiconductor transmission line (MTL) model will be described and the programmed equations will be derived. This model is exact in the sense that interactions between all conductors in the transmission line are considered, and the distributed parameter representation (assuming the TEM mode or "quasi-TEM" mode of propagation on the line) is used. The line is assumed to be uniform in the sense that all conductors are parallel to each other and there is no variation in the cross sections of the conductors or the surrounding media along the line.

2.1 The Multiconductor Transmission Line (MTL) Model

The MTL model is described in detail in Volume I of this series [1] and in reference [2]. In this section, a brief review of the MTL model will be given and the reader should consult Volume I [1] or reference [2] for further details.

If the line is immersed in a homogeneous medium, e.g., bare wires in free space, the fundamental mode of propagation is the TEM (Transverse Electro-Magnetic) mode. If the line is immersed in an inhomogeneous medium, e.g., wires with cylindrical dielectric insulations surrounded by free space, the fundamental mode of propagation is taken to be the "quasi-TEM" mode. The essential difference in these two cases is as follows. For lines in a homogeneous medium the TEM mode assumption is legitimate. For lines in an inhomogeneous medium, the TEM mode cannot exist except in the limiting case of zero frequency (DC). However, for the inhomogeneous medium case, the assumption is made that the electric and magnetic fields are almost trans-

verse to the direction of propagation, i.e., the mode of propagation is almost TEM or "quasi-TEM".

With the assumption of the TEM mode or "quasi-TEM" mode of propagation, line voltages and currents may be defined. Consider a general (n + 1) conductor, uniform transmission line shown in Figure 2-1. The (n + 1)st or zero-th conductor is the reference conductor for the line voltages. For sinusoidal, steady-state excitation of the line, the line voltages, $\mathcal{V}_i(x,t)$, (with respect to the reference, the zero-th, conductor) and line currents, $\mathcal{I}_i(x,t)$ are

$$\mathcal{V}_i(x,t) = V_i(x)\ e^{j\omega t} \tag{2-1a}$$

$$\mathcal{I}_i(x,t) = I_i(x)\ e^{j\omega t} \tag{2-1b}$$

for $i = 1, ---, n$ where $V_i(x)$ and $I_i(x)$ are the complex, phasor line voltages and currents and ω is the radian frequency of excitation of the line, $\omega = 2\pi f$. The current in the reference conductor satifies

$$\mathcal{I}_0(x,t) = -\sum_{i=1}^{n} \mathcal{I}_i(x,t) \tag{2-2a}$$

$$\check{I}_0(x) = -\sum_{i=1}^{n} I_i(x) \tag{2-2b}$$

The MTL equations can be derived from the per-unit-length equivalent circuit in Figure 2-2 and are a set of 2n, complex-valued, first order, ordinary differential equations

$$\frac{d}{dx}\begin{bmatrix}\underline{V}(x)\\ \underline{I}(x)\end{bmatrix} = -\begin{bmatrix}\underset{\sim}{0}_{n\times n} & \underset{\sim}{Z}\\ \underset{\sim}{Y} & \underset{\sim}{0}_{n\times n}\end{bmatrix}\begin{bmatrix}\underline{V}(x)\\ \underline{I}(x)\end{bmatrix} + \begin{bmatrix}\underline{V}_s(x)\\ \underline{I}_s(x)\end{bmatrix} \tag{2-3}$$

A matrix $\underset{\sim}{M}$ with m rows and p columns is said to be $m\chi p$ and the element in the i-th row and j-th column is designated by $[\underset{\sim}{M}]_{ij}$ with $i = 1, ---, m$

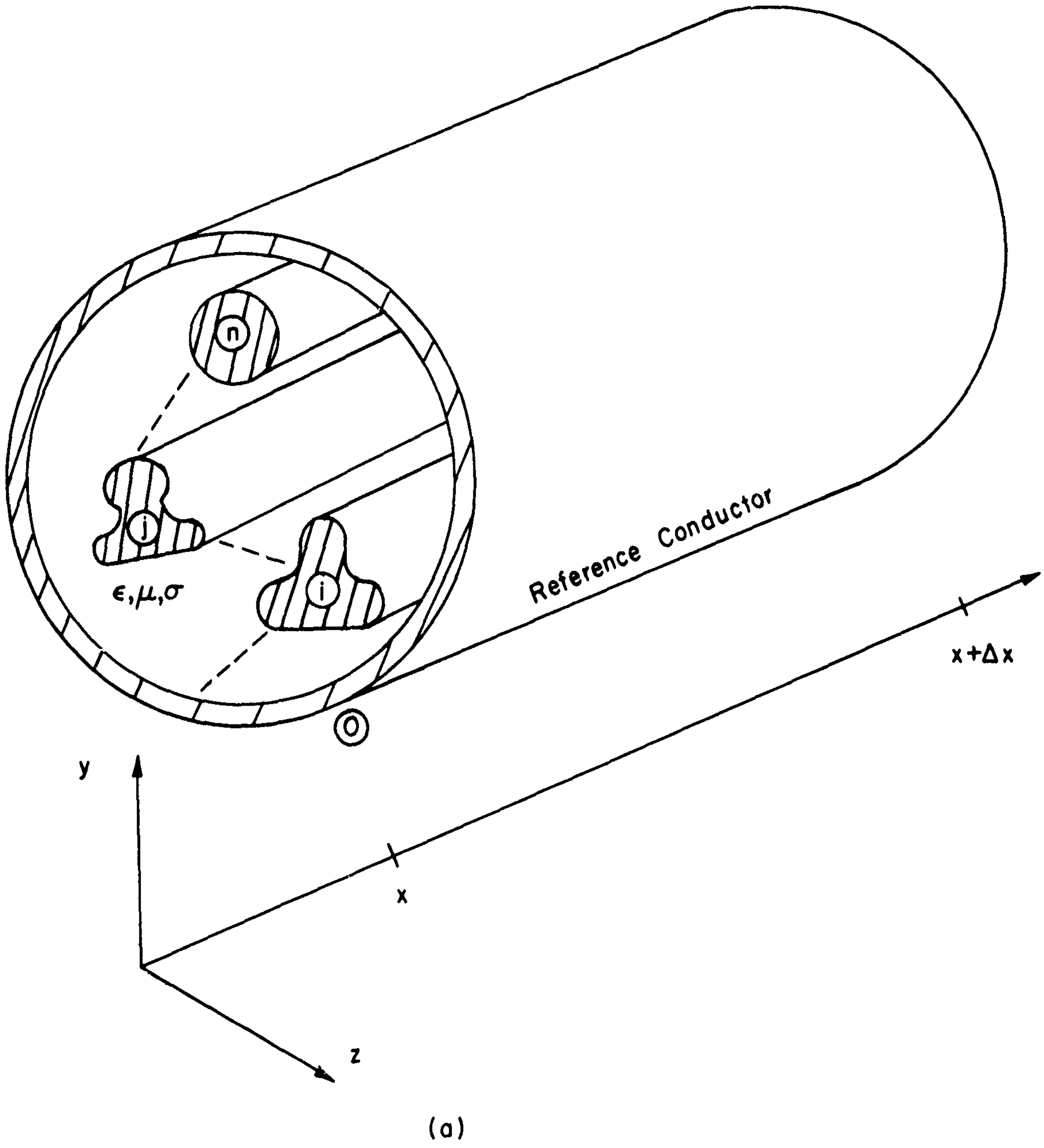


Fig. 2-1(cont.). An (n+1) conductor, uniform transmission line.

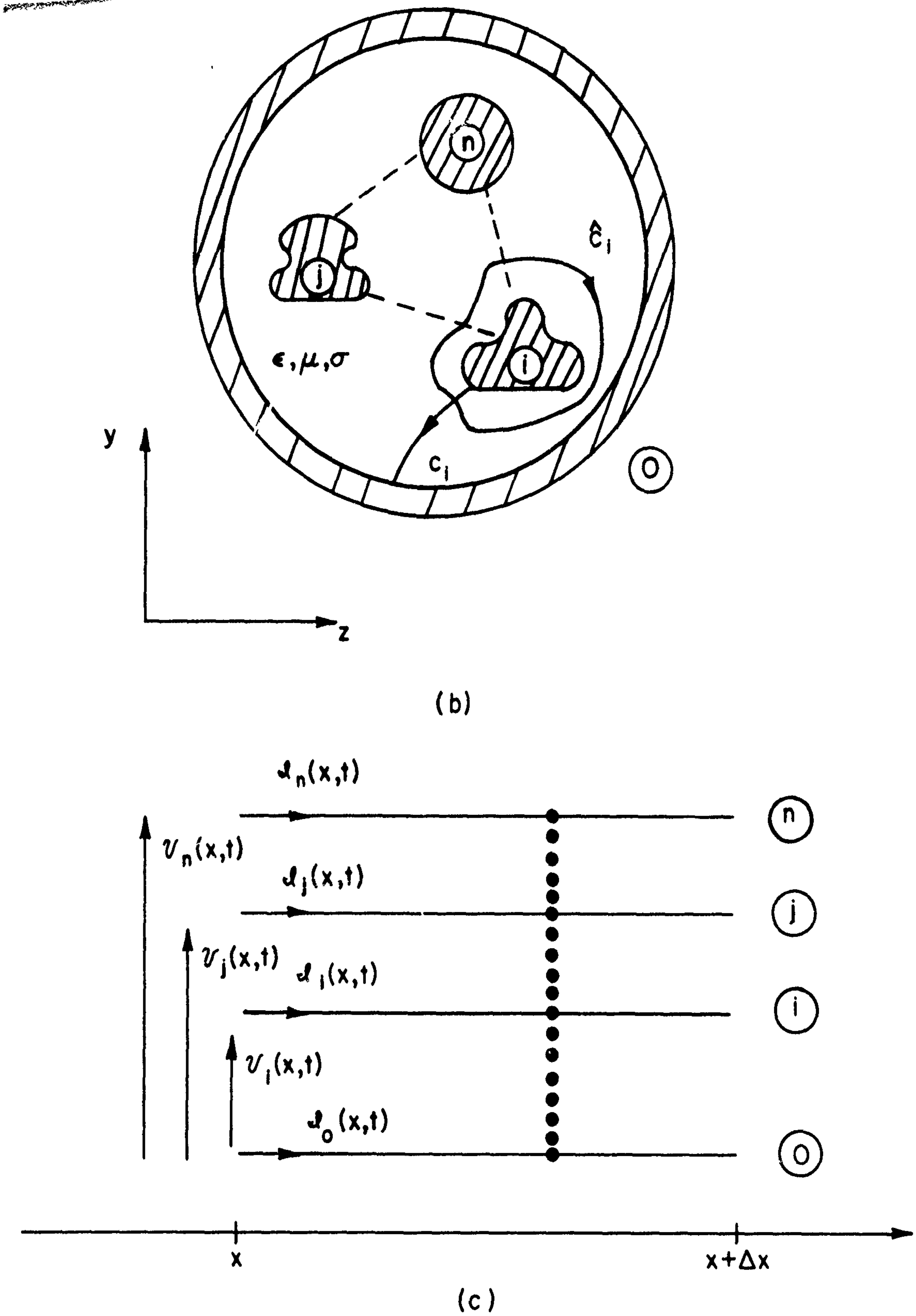


Fig. 2-1. An (n+1) conductor, uniform transmission line.

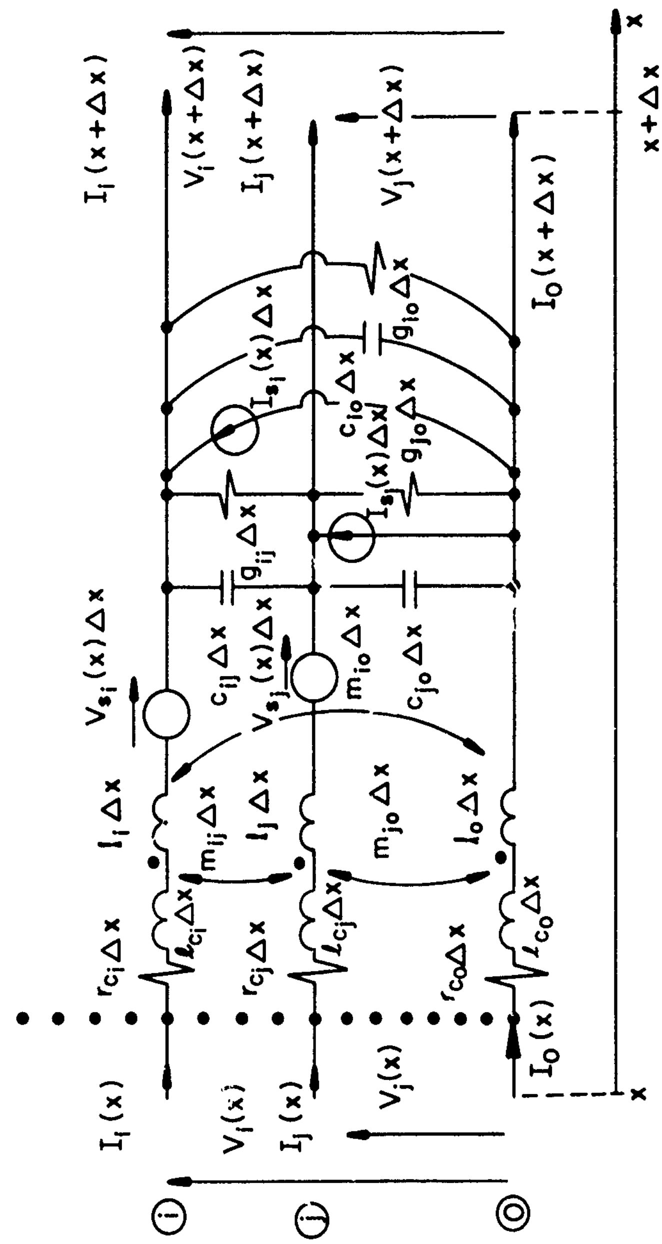


Fig. 2-2. The per-unit-length equivalent circuit.

and j = 1, ---, p. An $n\chi 1$ vector is denoted with a bar, e.g., $\underline{V}$, with the entry in the i-th row denoted by $[\underline{V}]_i = V_i$. The matrix $0_{m\sim p}$ is the $m\chi p$ zero matrix with zeros in every position, i.e., $[0_{m\sim p}]_{ij} = 0$ for i = 1, ---, m and j = 1, ---, p. The complex-valued phasor line voltages with respect to the reference conductor (the zero-th conductor), $V_i(x)$, and line currents, $I_i(x)$, are given by $[\underline{V}(x)]_i = V_i(x)$ and $[\underline{I}(x)]_i = I_i(x)$.

The $n\chi n$ complex-valued, symmetric matrices, $\tilde{Z}$ and $\tilde{Y}$, are the per-unit-length impedance and admittance matrices of the line, respectively. Since the line is assumed to be uniform, these matrices are independent of x. These per-unit-length matrices are separable as

$$\tilde{Z} = \tilde{R}_c + j\omega \tilde{L}_c + j\omega \tilde{L} \tag{2-4a}$$

$$\tilde{Y} = \tilde{G} + j\omega \tilde{C} \tag{2-4b}$$

where the $n\chi n$ real, symmetric matrices $\tilde{R}_c$, $\tilde{L}_c$, $\tilde{L}$, $\tilde{G}$, $\tilde{C}$ are the per-unit-length conductor resistance, conductor internal inductance, external inductance, conductance and capacitance matrices, respectively. The entries in these matrices may be straightforwardly obtained in terms of the elements of the per-unit-length equivalent circuit in Figure 2-2 as

$$[\tilde{R}_c]_{ii} = r_{c_i} + r_{c_0}, \quad [\tilde{R}_c]_{\substack{ij \\ i\neq j}} = r_{c_0} \tag{2-5a}$$

$$[\tilde{L}_c]_{ii} = \ell_{c_i} + \ell_{c_0}, \quad [\tilde{L}_c]_{\substack{ij \\ i\neq j}} = \ell_{c_0} \tag{2-5b}$$

$$[\tilde{L}]_{ii} = \ell_i + \ell_0 - 2m_{i0}, \quad [\tilde{L}]_{\substack{ij \\ i\neq j}} = \ell_0 + m_{ij} - m_{i0} - m_{j0} \tag{2-5c}$$

$$[\tilde{G}]_{ii} = g_{i0} + \sum_{\substack{j=1 \\ i\neq j}}^{n} g_{ij}, \quad [\tilde{G}]_{\substack{ij \\ i\neq j}} = -g_{ij} \tag{2-5d}$$

$$[\underset{\sim}{C}]_{ii} = c_{i0} + \sum_{\substack{j=1 \\ i\neq j}}^{n} c_{ij}, \quad [\underset{\sim}{C}]_{\substack{ij \\ i\neq j}} = -c_{ij}. \tag{2-5e}$$

The nχ1 column vectors, $\underline{V}_s(x)$ and $\underline{I}_s(x)$ contain per-unit-length equivalent voltage and current sources, $[\underline{V}_s(x)]_i = V_{s_i}(x)$ and $[\underline{I}_s(x)]_i = I_{s_i}(x)$, which are included to represent the effects of the spectral components of incident electromagnetic field sources which illuminate the line. These entries are complex-valued functions of frequency and position, x, along the line. In this report, no external incident fields are considered and these sources are set equal to zero, i.e., $\underline{V}_s(x) = \underset{n-1}{0}$ and $\underline{I}_s(x) = \underset{n-1}{0}$.

The solution to (2-3) is

$$\begin{aligned}\begin{bmatrix}\underline{V}(x)\\ \underline{I}(x)\end{bmatrix} &= \underset{\sim}{\Phi}(x,x_0)\begin{bmatrix}\underline{V}(x_0)\\ \underline{I}(x_0)\end{bmatrix} + \int_{x_0}^{x} \underset{\sim}{\Phi}(x,\hat{x})\begin{bmatrix}\underline{V}_s(\hat{x})\\ \underline{I}_s(\hat{x})\end{bmatrix} d\hat{x} \\ &= \underset{\sim}{\Phi}(x,x_0)\begin{bmatrix}\underline{V}(x_0)\\ \underline{I}(x_0)\end{bmatrix} + \begin{bmatrix}\hat{\underline{V}}_s(x)\\ \hat{\underline{I}}_s(x)\end{bmatrix}\end{aligned} \tag{2-6}$$

where $\underset{\sim}{\Phi}(x,x_0)$ is the 2nχ2n chain parameter matrix (or state transition matrix) and x_0 is some arbitrary position along the line $x \geq x_0$. The chain parameter matrix can be partitioned as

$$\underset{\sim}{\Phi}(x,x_0) = \begin{bmatrix}\underset{\sim}{\Phi}_{11}(x,x_0) & \underset{\sim}{\Phi}_{12}(x,x_0)\\ \underset{\sim}{\Phi}_{21}(x,x_0) & \underset{\sim}{\Phi}_{22}(x,x_0)\end{bmatrix} \tag{2-7}$$

where $\underset{\sim}{\Phi}_{ij}(x,x_0)$ are nχn for i, j=1, 2. Thus (2-6) can be written as

$$\underline{V}(x) = \underset{\sim}{\Phi}_{11}(x,x_0)\,\underline{V}(x_0) + \underset{\sim}{\Phi}_{12}(x,x_0)\,\underline{I}(x_0) + \hat{\underline{V}}_s(x) \tag{2-8a}$$

$$\underline{I}(x) = \underset{\sim}{\Phi}_{21}(x,x_0)\,\underline{V}(x_0) + \underset{\sim}{\Phi}_{22}(x,x_0)\,\underline{I}(x_0) + \hat{\underline{I}}_s(x) \tag{2-8b}$$

The entries $\underset{\sim}{\Phi}_{ij}(x,x_0)$ are given by

$$\underset{\sim}{\Phi}_{11}(x,x_0) = 1/2\ \underset{\sim}{Y}^{-1}\ \underset{\sim}{T}\ (e^{\underset{\sim}{\gamma}(x-x_0)} + e^{-\underset{\sim}{\gamma}(x-x_0)})\ \underset{\sim}{T}^{-1}\ \underset{\sim}{Y} \tag{2-9a}$$

$$\underset{\sim}{\Phi}_{12}(x,x_0) = -1/2\ \underset{\sim}{Y}^{-1}\ \underset{\sim}{T}\ \underset{\sim}{\gamma}(e^{\underset{\sim}{\gamma}(x-x_0)} - e^{-\underset{\sim}{\gamma}(x-x_0)})\ \underset{\sim}{T}^{-1} \tag{2-9b}$$

$$\underset{\sim}{\Phi}_{21}(x,x_0) = -1/2\ \underset{\sim}{T}\ (e^{\underset{\sim}{\gamma}(x-x_0)} - e^{-\underset{\sim}{\gamma}(x-x_0)})\ \underset{\sim}{\gamma}^{-1}\ \underset{\sim}{T}^{-1}\ \underset{\sim}{Y} \tag{2-9c}$$

$$\underset{\sim}{\Phi}_{22}(x,x_0) = 1/2\ \underset{\sim}{T}\ (e^{\underset{\sim}{\gamma}(x-x_0)} + e^{-\underset{\sim}{\gamma}(x-x_0)})\ \underset{\sim}{T}^{-1} \tag{2-9d}$$

where $e^{\underset{\sim}{\gamma}(x-x_0)}$ is an $n\chi n$ diagonal matrix with $[e^{\underset{\sim}{\gamma}(x-x_0)}]_{ii} = e^{\gamma_i(x-x_0)}$ and $[e^{\underset{\sim}{\gamma}(x-x_0)}]_{ij} = 0$ for i, j=1, ---, n and $i \neq j$. The matrix $\underset{\sim}{T}$ is an $n\chi n$, complex-valued matrix which diagonalizes the matrix product $\underset{\sim}{Y}\underset{\sim}{Z}$ as

$$\underset{\sim}{T}^{-1}\ \underset{\sim}{Y}\ \underset{\sim}{Z}\ \underset{\sim}{T} = \underset{\sim}{\gamma}^2 \tag{2-10}$$

where $\underset{\sim}{\gamma}^2$ is an $n\chi n$ diagonal matrix with $[\underset{\sim}{\gamma}^2]_{ii} = \gamma_i^{\ 2}$ and $[\underset{\sim}{\gamma}^2]_{ij} = 0$ for i, j=1, ---, n and $i \neq j$. The $n\chi n$ characteristic impedance matrix, $\underset{\sim}{Z}_C$, is given by

$$\underset{\sim}{Z}_C = \underset{\sim}{Y}^{-1}\ \underset{\sim}{T}\ \underset{\sim}{\gamma}\ \underset{\sim}{T}^{-1} = \underset{\sim}{Z}\ \underset{\sim}{T}\ \underset{\sim}{\gamma}^{-1}\ \underset{\sim}{T}^{-1} \tag{2-11}$$

The transmission line is of length $\mathcal{L}$ with termination networks at x = 0 and at x = $\mathcal{L}$ as shown in Fig. 2-3. For generality, the termination networks are considered to be in the form of linear n-ports and are characterizable by "Generalized Thevenin Equivalents" as

$$\underline{V}(0) = \underline{V}_0 - \underset{\sim}{Z}_0\ \underline{I}(0) \tag{2-12a}$$

$$\underline{V}(\mathcal{L}) = \underline{V}_{\mathcal{L}} + \underset{\sim}{Z}_{\mathcal{L}}\ \underline{I}(\mathcal{L}) \tag{2-12b}$$

where $\underline{V}_0$ and $\underline{V}_{\mathcal{L}}$ are $n\chi 1$ complex-valued vectors of equivalent, open-circuit, port excitation voltages (with respect to the reference conductor) and $\underset{\sim}{Z}_0$

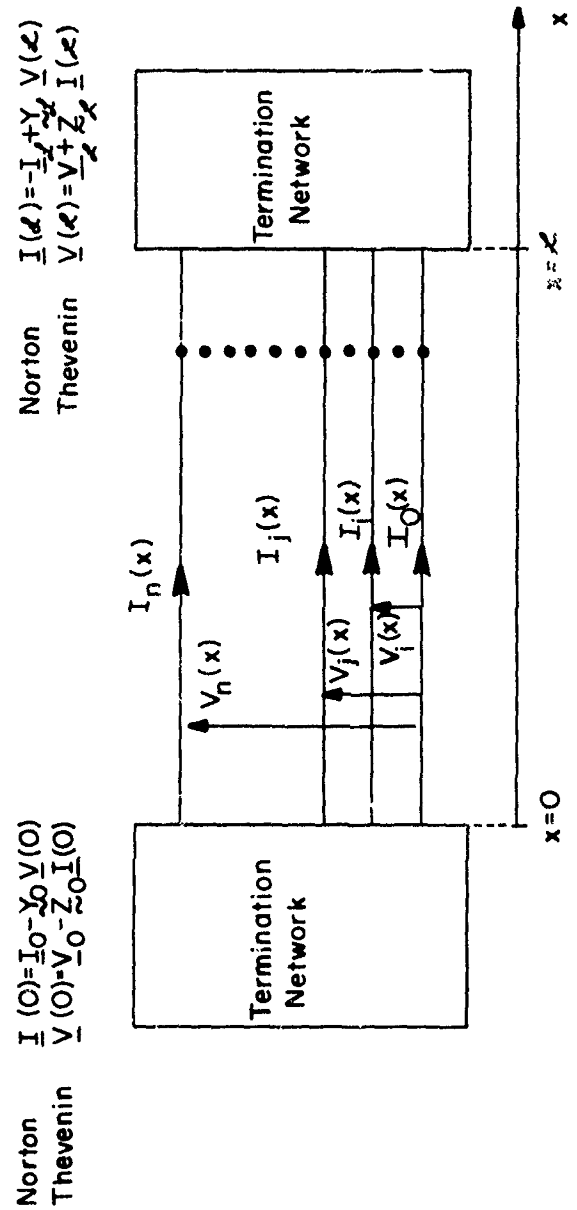


Fig. 2-3. The termination networks.

and $\underset{\sim}{Z}_{\mathcal{L}}$ are nχn symmetric, complex-valued port impedance matrices.

As an alternate characterization, (2-12) may be written as "Generalized Norton Equivalents" by multiplying (2-12a) on the left by $\underset{\sim}{Z}_0^{-1}$ and (2-12b) on the left by $\underset{\sim}{Z}_{\mathcal{L}}^{-1}$ and rearranging as

$$\underline{I}(0) = \underline{I}_0 - \underset{\sim}{Y}_0\, \underline{V}(0) \tag{2-13a}$$

$$\underline{I}(\mathcal{L}) = -\underline{I}_{\mathcal{L}} + \underset{\sim}{Y}_{\mathcal{L}}\, \underline{V}(\mathcal{L}) \tag{2-13b}$$

where $\underline{I}_0$ and $\underline{I}_{\mathcal{L}}$ are equivalent, short-circuit, port excitation current sources. The nχn port admittance matrices $\underset{\sim}{Y}_0$ and $\underset{\sim}{Y}_{\mathcal{L}}$ are given by $\underset{\sim}{Y}_0 = \underset{\sim}{Z}_0^{-1}$ and $\underset{\sim}{Y}_{\mathcal{L}} = \underset{\sim}{Z}_{\mathcal{L}}^{-1}$ where the inverse of an nχn matrix $\underset{\sim}{M}$ is denoted by $\underset{\sim}{M}^{-1}$ and $\underline{I}_0 = \underset{\sim}{Y}_0\, \underline{V}_0$, $\underline{I}_{\mathcal{L}} = \underset{\sim}{Y}_{\mathcal{L}}\, \underline{V}_{\mathcal{L}}$. These port admittance matrices can be found by treating the line currents $\underline{I}(0)$ or $\underline{I}(\mathcal{L})$ as independent sources and writing the node voltage equations for the termination networks. The transmission line voltages, $\underline{V}(0)$ or $\underline{V}(\mathcal{L})$, will comprise subsets of the node voltages of the termimation networks. The additional node voltages can be eliminated from the node voltage equations describing the networks to yield (2-13). If the termination networks at $x = 0$ and $x = \mathcal{L}$ consist only of admittances between the i-th and j-th wires, $Y_{0_{ij}}$ and $Y_{\mathcal{L}_{ij}}$, respectively, and between the i-th wire and the reference conductor, $Y_{0_{ii}}$ and $Y_{\mathcal{L}_{ii}}$, respectively, then the entries in $\underset{\sim}{Y}_0$ and $\underset{\sim}{Y}_{\mathcal{L}}$ become $[\underset{\sim}{Y}_0]_{ii} = Y_{0_{ii}} + \sum_{j=1}^{n} Y_{0_{ij}}$, $[\underset{\sim}{Y}_0]_{ij} = -Y_{0_{ij}}$, $[\underset{\sim}{Y}_{\mathcal{L}}]_{ii} = Y_{\mathcal{L}_{ii}} + \sum_{j=1}^{n} Y_{\mathcal{L}_{ij}}$, $[\underset{\sim}{Y}_{\mathcal{L}}]_{ij} = -Y_{\mathcal{L}_{ij}}$ for i, j=1, ---, n and $i \neq j$.

With $x = \mathcal{L}$ and $x_0 = 0$ in (2-8), one can straightforwardly obtain using the"Generalized Thevenin Equivalent" characterization of the termination networks given in (2-12)[2]

[2] In (2-8a) with $x=\mathcal{L}, x_0=0$ substitute (2-12a) for $\underline{V}(0)$ and (2-12b) for $\underline{V}(\mathcal{L})$. Then substitute $\underline{I}(\mathcal{L})$ from (2-8b) with $x=\mathcal{L}, x_0=0$ into the result and rearrange into the form in (2-14a). Substitute $\underline{V}(0)$ from (2-12a) into (2-8b) and rearrange to yield (2-14b).

$$[\underset{\sim}{Z}_{\mathcal{L}}\underset{\sim}{\Phi}_{22}(\mathcal{L}) - \underset{\sim}{Z}_{\mathcal{L}}\underset{\sim}{\Phi}_{21}(\mathcal{L})\underset{\sim}{Z}_0 - \underset{\sim}{\Phi}_{12}(\mathcal{L}) + \underset{\sim}{\Phi}_{11}(\mathcal{L})\underset{\sim}{Z}_0]\,\underline{I}(0) =$$

$$[\underset{\sim}{\Phi}_{11}(\mathcal{L}) - \underset{\sim}{Z}_{\mathcal{L}}\underset{\sim}{\Phi}_{21}(\mathcal{L})]\,\underline{V}_0 - \underline{V}_{\mathcal{L}} + \underline{\hat{V}}_s(\mathcal{L}) - \underset{\sim}{Z}_{\mathcal{L}}\underline{\hat{I}}_s(\mathcal{L}) \qquad (2\text{-}14a)$$

$$\underline{I}(\mathcal{L}) = \underset{\sim}{\Phi}_{21}(\mathcal{L})\,\underline{V}_0 + [\underset{\sim}{\Phi}_{22}(\mathcal{L}) - \underset{\sim}{\Phi}_{21}(\mathcal{L})\underset{\sim}{Z}_0]\,\underline{I}(0) + \underline{\hat{I}}_s(\mathcal{L}) \qquad (2\text{-}14b)$$

where $\underset{\sim}{\Phi}(\mathcal{L},0) \triangleq \underset{\sim}{\Phi}(\mathcal{L})$. $\underline{V}(x)$ and $\underline{I}(x)$ can be obtained for any x, $0 \le x \le \mathcal{L}$, from (2-8) with $\underline{I}(0)$ from the solution of (2-14a) and $\underline{V}(0)$ determined from (2-12a). Generally, we are only interested in the terminal voltages and currents, $\underline{V}(0)$, $\underline{V}(\mathcal{L})$, $\underline{I}(0)$, $\underline{I}(\mathcal{L})$. The terminal currents, $\underline{I}(0)$ and $\underline{I}(\mathcal{L})$, can be obtained from (2-14) and the terminal voltages, $\underline{V}(0)$ and $\underline{V}(\mathcal{L})$, can be obtained from (2-12). Here one only needs to solve n equations in n unknowns (equation 2-14a)).

The $\underset{\sim}{\Phi}_{ij}$ submatrices of the chain parameter matrix in (2-7) satisfy certain fundamental identities, [1,2]. These identities can be used to formulate (2-14a) in an alternate form [1,2]:

$$[\{\underset{\sim}{\Phi}_{21}(\mathcal{L})\underset{\sim}{Z}_{\mathcal{L}} - \underset{\sim}{\Phi}_{22}(\mathcal{L})\}\ \{\underset{\sim}{\Phi}_{21}(\mathcal{L})\underset{\sim}{Z}_0 - \underset{\sim}{\Phi}_{22}(\mathcal{L})\} - \underset{\sim}{1}_n]\,\underline{I}(0) =$$

$$\underset{\sim}{\Phi}_{21}(\mathcal{L})\,\underline{V}_{\mathcal{L}} + \{\underset{\sim}{\Phi}_{21}(\mathcal{L})\underset{\sim}{Z}_{\mathcal{L}} - \underset{\sim}{\Phi}_{22}(\mathcal{L})\}\,\underset{\sim}{\Phi}_{21}(\mathcal{L})\,\underline{V}_0 - \underset{\sim}{\Phi}_{21}(\mathcal{L})\,\cdot$$

$$[\underline{\hat{V}}_s(\mathcal{L}) - \underset{\sim}{Z}_{\mathcal{L}}\underline{\hat{I}}_s(\mathcal{L})] \qquad (2\text{-}15)$$

where $\underset{\sim}{1}_n$ is the nxn identity matrix with $[\underset{\sim}{1}_n]_{ii} = 1$ and $[\underset{\sim}{1}_n]_{ij} = 0$ for i, j=1, ---, n and $i \neq j$. Note that the formulations in (2-15) and (2-14b) require computation of only two of the four chain parameter submatrices, $\underset{\sim}{\Phi}_{21}(\mathcal{L})$ and $\underset{\sim}{\Phi}_{22}(\mathcal{L})$.

As an alternate formulation, the above equations can be written in terms

of the "Generalized Norton Equivalent" representation of the termination networks given in (2-13). Rather than rederiving the above equations it is much simpler to note the direct similarity of the Norton equivalent representation in (2-13) and the Thevenin equivalent representation in (2-12). By noting the analogous variables in (2-13) and (2-12) and observing the form of (2-8), we may simply make certain substitutions of these analogous variables in (2-14) and (2-15) as shown in Table 1. The result is

$$\begin{aligned}
&[\underset{\sim}{Y}_{\mathcal{L}}\underset{\sim}{\Phi}_{11}(\mathcal{L}) - \underset{\sim}{Y}_{\mathcal{L}}\underset{\sim}{\Phi}_{12}(\mathcal{L})\,\underset{\sim}{Y}_0 - \underset{\sim}{\Phi}_{21}(\mathcal{L}) + \underset{\sim}{\Phi}_{22}(\mathcal{L})\,\underset{\sim}{Y}_0]\,\underline{V}(0) = \\
&[\underset{\sim}{\Phi}_{22}(\mathcal{L}) - \underset{\sim}{Y}_{\mathcal{L}}\underset{\sim}{\Phi}_{12}(\mathcal{L})]\,\underline{I}_0 + \underline{I}_{\mathcal{L}} + \hat{\underline{I}}_s(\mathcal{L}) - \underset{\sim}{Y}_{\mathcal{L}}\hat{\underline{V}}_s(\mathcal{L})
\end{aligned} \tag{2-16a}$$

$$\underline{V}(\mathcal{L}) = \underset{\sim}{\Phi}_{12}(\mathcal{L})\,\underline{I}_0 + [\underset{\sim}{\Phi}_{11}(\mathcal{L}) - \underset{\sim}{\Phi}_{12}(\mathcal{L})\,\underset{\sim}{Y}_0]\,\underline{V}(0) + \hat{\underline{V}}_s(\mathcal{L}) \tag{2-16b}$$

$$\begin{aligned}
&[\{\underset{\sim}{\Phi}_{12}(\mathcal{L})\,\underset{\sim}{Y}_{\mathcal{L}} - \underset{\sim}{\Phi}_{11}(\mathcal{L})\}\{\underset{\sim}{\Phi}_{12}(\mathcal{L})\,\underset{\sim}{Y}_0 - \underset{\sim}{\Phi}_{11}(\mathcal{L})\} - \underset{\sim}{1}_n]\,\underline{V}(0) = \\
&- \underset{\sim}{\Phi}_{12}(\mathcal{L})\,\underline{I}_{\mathcal{L}} + [\underset{\sim}{\Phi}_{12}(\mathcal{L})\,\underset{\sim}{Y}_{\mathcal{L}} - \underset{\sim}{\Phi}_{11}(\mathcal{L})]\,\underset{\sim}{\Phi}_{12}(\mathcal{L})\,\underline{I}_0 \\
&- \underset{\sim}{\Phi}_{12}(\mathcal{L})\,[\hat{\underline{I}}_s(\mathcal{L}) - \underset{\sim}{Y}_{\mathcal{L}}\hat{\underline{V}}_s(\mathcal{L})]
\end{aligned} \tag{2-16c}$$

2.2 The Equations to Be Programmed

The equations for $\underline{I}(\mathcal{L})$ and $\underline{V}(\mathcal{L})$ are given in (2-14b) and (2-16b), respectively. Either (2-14a) or (2-15) could be used for determining $\underline{I}(0)$ and either (2-16a) or (2-16c) could be used for determining $\underline{V}(0)$. However, (2-14a) and (2-16a) will be selected for determining $\underline{I}(0)$ and $\underline{V}(0)$, respectively. Since no external incident fields are considered, $\hat{\underline{V}}_s(\mathcal{L})$ and $\hat{\underline{I}}_s(\mathcal{L})$ in (2-14), (2-15) and (2-16) will be zero, i.e., $\hat{\underline{V}}_s(\mathcal{L}) = \hat{\underline{I}}_s(\mathcal{L}) = {}_n0_1$.

Certain modifications to these equations will be made to produce the final equations. The matrix chain parameters given in (2-9) for a line of

TABLE 1

Analogous variables in the Generalized Thevenin Equivalent (2-12) and Generalized Norton Equivalent (2-13) representation of the termination networks. The analogous variables are substituted in equations (2-14) and (2-15) to obtain equations (2-16).

Generalized Thevenin Equivalent (2-12)	Generalized Norton Equivalent (2-13)
$\underline{I}(0)$	$\underline{V}(0)$
$\underline{I}(\ell)$	$\underline{V}(\ell)$
$\underset{\sim}{Z}_0$	$\underset{\sim}{Y}_0$
$\underset{\sim}{Z}_\ell$	$\underset{\sim}{Y}_\ell$
$\underline{V}(0)$	$\underline{I}(0)$
$\underline{V}(\ell)$	$-\underline{I}(\ell)$
$\underset{\sim}{\Phi}_{11}(\ell)$	$\underset{\sim}{\Phi}_{22}(\ell)$
$\underset{\sim}{\Phi}_{12}(\ell)$	$\underset{\sim}{\Phi}_{21}(\ell)$
$\underset{\sim}{\Phi}_{21}(\ell)$	$\underset{\sim}{\Phi}_{12}(\ell)$
$\underset{\sim}{\Phi}_{22}(\ell)$	$\underset{\sim}{\Phi}_{11}(\ell)$
$\hat{\underline{V}}_s(\ell)$	$\hat{\underline{I}}_s(\ell)$
$\hat{\underline{I}}_s(\ell)$	$\hat{\underline{V}}_s(\ell)$

total length $\ell(x_0 = 0,\ x = \ell)$ become

$$\underset{\sim}{\Phi}_{11}(\ell) = \underset{\sim}{Y}^{-1}\ \underset{\sim}{T}\ \underset{\sim}{E}^{+}\ \underset{\sim}{T}^{-1}\ \underset{\sim}{Y} \tag{2-17a}$$

$$\underset{\sim}{\Phi}_{12}(\ell) = -\underset{\sim}{Y}^{-1}\ \underset{\sim}{T}\ \underset{\sim}{\gamma}\ \underset{\sim}{E}^{-}\ \underset{\sim}{T}^{-1} \tag{2-17b}$$

$$\underset{\sim}{\Phi}_{21}(\ell) = -\underset{\sim}{T}\ \underset{\sim}{E}^{-}\ \underset{\sim}{\gamma}^{-1}\ \underset{\sim}{T}^{-1}\underset{\sim}{Y} \tag{2-17c}$$

$$\underset{\sim}{\Phi}_{22}(\ell) = \underset{\sim}{T}\ \underset{\sim}{E}^{+}\ \underset{\sim}{T}^{-1} \tag{2-17d}$$

where the nχn diagonal matrices $\underset{\sim}{E}^{+}$ and $\underset{\sim}{E}^{-}$ are given by

$$\underset{\sim}{E}^{+} = \frac{1}{2}\left(e^{\underset{\sim}{\gamma}\ell} + e^{-\underset{\sim}{\gamma}\ell}\right) \tag{2-18a}$$

$$\underset{\sim}{E}^{-} = \frac{1}{2}\left(e^{\underset{\sim}{\gamma}\ell} - e^{-\underset{\sim}{\gamma}\ell}\right) \tag{2-18b}$$

Substituting (2-17) into (2-14a) and (2-14b) yields, for the Thevenin Equivalent representation of the termination networks

$$\begin{aligned}&[\underset{\sim}{Z}_{\ell}\ \underset{\sim}{T}\ \underset{\sim}{E}^{+}\ \underset{\sim}{T}^{-1} + \underset{\sim}{Z}_{\ell}\underset{\sim}{T}\ \underset{\sim}{E}^{-}\ \underset{\sim}{\gamma}^{-1}\ \underset{\sim}{T}^{-1}\ \underset{\sim}{Y}\ \underset{\sim}{Z}_0\\ &+ \underset{\sim}{Y}^{-1}\ \underset{\sim}{T}\ \underset{\sim}{\gamma}\ \underset{\sim}{E}^{-}\ \underset{\sim}{T}^{-1} + \underset{\sim}{Y}^{-1}\ \underset{\sim}{T}\ \underset{\sim}{E}^{+}\ \underset{\sim}{T}^{-1}\ \underset{\sim}{Y}\ \underset{\sim}{Z}_0]\ \underline{I}(0)\\ &= [\underset{\sim}{Y}^{-1}\ \underset{\sim}{T}\ \underset{\sim}{E}^{+}\ \underset{\sim}{T}^{-1}\ \underset{\sim}{Y} + \underset{\sim}{Z}_{\ell}\ \underset{\sim}{T}\ \underset{\sim}{E}^{-}\ \underset{\sim}{\gamma}^{-1}\ \underset{\sim}{T}^{-1}\ \underset{\sim}{Y}]\ \underline{V}_0 - \underline{V}_{\ell}\end{aligned} \tag{2-19a}$$

$$\begin{aligned}&\underline{I}(\ell) = -\underset{\sim}{T}\ \underset{\sim}{E}^{-}\ \underset{\sim}{\gamma}^{-1}\ \underset{\sim}{T}^{-1}\ \underset{\sim}{Y}\ \underline{V}_0\\ &+ [\underset{\sim}{T}\ \underset{\sim}{E}^{+}\ \underset{\sim}{T}^{-1} + \underset{\sim}{T}\ \underset{\sim}{E}^{-}\ \underset{\sim}{\gamma}^{-1}\ \underset{\sim}{T}^{-1}\ \underset{\sim}{Y}\ \underset{\sim}{Z}_0]\ \underline{I}(0)\end{aligned} \tag{2-19b}$$

Similarly, substituting (2-17) into (2-16a) and (2-16b) yields, for the Norton Equivalent representation of the termination networks,

$$\begin{aligned}&[\underset{\sim}{Y}_{\ell}\underset{\sim}{Y}^{-1}\ \underset{\sim}{T}\ \underset{\sim}{E}^{+}\ \underset{\sim}{T}^{-1}\ \underset{\sim}{Y} + \underset{\sim}{Y}_{\ell}\underset{\sim}{Y}^{-1}\ \underset{\sim}{T}\ \underset{\sim}{\gamma}\ \underset{\sim}{E}^{-}\ \underset{\sim}{T}^{-1}\ \underset{\sim}{Y}_0\\ &+ \underset{\sim}{T}\ \underset{\sim}{E}^{-}\ \underset{\sim}{\gamma}^{-1}\ \underset{\sim}{T}^{-1}\ \underset{\sim}{Y} + \underset{\sim}{T}\ \underset{\sim}{E}^{+}\ \underset{\sim}{T}^{-1}\ \underset{\sim}{Y}_0]\ \underline{V}(0)\\ &= [\underset{\sim}{T}\ \underset{\sim}{E}^{+}\ \underset{\sim}{T}^{-1} + \underset{\sim}{Y}_{\ell}\ \underset{\sim}{Y}^{-1}\ \underset{\sim}{T}\ \underset{\sim}{\gamma}\ \underset{\sim}{E}^{-}\ \underset{\sim}{T}^{-1}]\ \underline{I}_0 + \underline{I}_{\ell}\end{aligned} \tag{2-20a}$$

$$\underline{V}(\ell) = -\underset{\sim}{Y}^{-1}\ \underset{\sim}{T}\ \underset{\sim}{\gamma}\ \underset{\sim}{E}^{-}\ \underset{\sim}{T}^{-1}\ \underline{I}_0 + [\underset{\sim}{Y}^{-1}\ \underset{\sim}{T}\ \underset{\sim}{E}^{+}\ \underset{\sim}{T}^{-1}\ \underset{\sim}{Y} + \underset{\sim}{Y}^{-1}\ \underset{\sim}{T}\ \underset{\sim}{\gamma}\ \underset{\sim}{E}^{-}\ \underset{\sim}{T}^{-1}\ \underset{\sim}{Y}_0]\underline{V}(0) \tag{2-20b}$$

The medium surrounding all conductors is assumed throughout this report to be lossless. Therefore the per-unit-length conductance matrix, $\underset{\sim}{G}$,which represents these losses in (2-4b) is zero, i.e., $\underset{\sim}{G} = \underset{n\sim n}{0}$. Therefore the per-unit-length admittance matrix becomes

$$\underset{\sim}{Y} = j\,\omega\,\underset{\sim}{C} \tag{2-21}$$

The per-unit-length impedance matrix is

$$\underset{\sim}{Z} = \underset{\sim}{R}_c + j\,\omega\,\underset{\sim}{L}_c + j\,\omega\,\underset{\sim}{L} \tag{2-22}$$

where $\underset{\sim}{R}_c$ and $\underset{\sim}{L}_c$ are zero matrices, i.e., $\underset{n\sim n}{0}$, when perfect conductors are assumed.

To reduce the number of matrix multiplications, the above equations will be placed in an alternate form. For the Norton Equivalent representation in (2-20),define

$$\underset{\sim}{Y}^*_{\ell} = \underset{\sim}{T}^{-1}\,\underset{\sim}{Y}_{\ell}\,\underset{\sim}{C}^{-1}\,\underset{\sim}{T} \tag{2-23a}$$

$$\underset{\sim}{Y}^*_0 = \underset{\sim}{T}^{-1}\,\underset{\sim}{Y}_0\,\underset{\sim}{C}^{-1}\,\underset{\sim}{T} \tag{2-23b}$$

$$\underline{V}^*(\ell) = \underset{\sim}{T}^{-1}\,\underset{\sim}{C}\,\underline{V}(\ell) \tag{2-23c}$$

$$\underline{V}^*(0) = \underset{\sim}{T}^{-1}\,\underset{\sim}{C}\,\underline{V}(0) \tag{2-23d}$$

$$\underline{I}^*_{\ell} = \underset{\sim}{T}^{-1}\,\underline{I}_{\ell} \tag{2-23e}$$

$$\underline{I}^*_0 = \underset{\sim}{T}^{-1}\,\underline{I}_0 \tag{2-23f}$$

$$\underset{\sim}{\gamma} = j\,\omega\,\underset{\sim}{\Lambda} \tag{2-23g}$$

Equations (2-20) can then be written as

$$\begin{aligned}&[\underset{\sim}{Y}^*_{\ell}\,\underset{\sim}{E}^+ + \underset{\sim}{Y}^*_{\ell}\,\underset{\sim}{\Lambda}\,\underset{\sim}{E}^-\,\underset{\sim}{Y}^*_0 + \underset{\sim}{E}^-\,\underset{\sim}{\Lambda}^{-1} + \underset{\sim}{E}^+\,\underset{\sim}{Y}^*_0]\,\underline{V}^*(0)\\ &= [\underset{\sim}{E}^+ + \underset{\sim}{Y}^*_{\ell}\,\underset{\sim}{\Lambda}\,\underset{\sim}{E}^-]\,\underline{I}^*_0 + \underline{I}^*_{\ell}\end{aligned} \tag{2-24a}$$

$$\underline{V}^*(\ell) = -\underset{\sim}{\Lambda}\,\underset{\sim}{E}^-\,\underline{I}_0^* + [\underset{\sim}{E}^+ + \underset{\sim}{\Lambda}\,\underset{\sim}{E}^-\,\underset{\sim}{Y}_0^*]\,\underline{V}^*(0) \tag{2-24b}$$

and the actual termination voltages can be determined by solving (2-24) for $\underline{V}^*(0)$ and $\underline{V}^*(\ell)$ and using (2-23c) and (2-23d) to obtain

$$\underline{V}(0) = \underset{\sim}{C}^{-1}\,\underset{\sim}{T}\,\underline{V}^*(0) \tag{2-25a}$$

$$\underline{V}(\ell) = \underset{\sim}{C}^{-1}\,\underset{\sim}{T}\,\underline{V}^*(\ell) \tag{2-25b}$$

These equations are summarized in Table 2.

Similarly, equations (2-19) for the Thevenin Equivalent representation of the terminal networks can be reduced to an equivalent form by defining

$$\underset{\sim}{Z}_\ell^* = \underset{\sim}{T}^{-1}\,\underset{\sim}{C}\,\underset{\sim}{Z}_\ell\,\underset{\sim}{T} \tag{2-26a}$$

$$\underset{\sim}{Z}_0^* = \underset{\sim}{T}^{-1}\,\underset{\sim}{C}\,\underset{\sim}{Z}_0\,\underset{\sim}{T} \tag{2-26b}$$

$$\underline{I}^*(\ell) = \underset{\sim}{T}^{-1}\,\underline{I}(\ell) \tag{2-26c}$$

$$\underline{I}^*(0) = \underset{\sim}{T}^{-1}\,\underline{I}(0) \tag{2-26d}$$

$$\underline{V}_\ell^* = \underset{\sim}{T}^{-1}\,\underset{\sim}{C}\,\underline{V}_\ell \tag{2-26e}$$

$$\underline{V}_0^* = \underset{\sim}{T}^{-1}\,\underset{\sim}{C}\,\underline{V}_0 \tag{2-26f}$$

$$\underset{\sim}{\gamma} = j\,\omega\,\underset{\sim}{\Lambda} \tag{2-26g}$$

Equations (2-19) can then be written as

$$\begin{aligned}[\underset{\sim}{Z}_\ell^*\,\underset{\sim}{E}^+ + \underset{\sim}{Z}_\ell^*\,\underset{\sim}{E}^-\,\underset{\sim}{\Lambda}^{-1}\,\underset{\sim}{Z}_0^* + \underset{\sim}{\Lambda}\,\underset{\sim}{E}^- + \underset{\sim}{E}^+\,\underset{\sim}{Z}_0^*]\,\underline{I}^*(0)& \\ = [\underset{\sim}{E}^+ + \underset{\sim}{Z}_\ell^*\,\underset{\sim}{E}^-\,\underset{\sim}{\Lambda}^{-1}]\,\underline{V}_0^* - \underline{V}_\ell^*&\end{aligned} \tag{2-27a}$$

$$\underline{I}^*(\ell) = -\underset{\sim}{E}^-\,\underset{\sim}{\Lambda}^{-1}\,\underline{V}_0^* + [\underset{\sim}{E}^+ + \underset{\sim}{E}^-\,\underset{\sim}{\Lambda}^{-1}\,\underset{\sim}{Z}_0^*]\,\underline{I}^*(0) \tag{2-27b}$$

and the actual termination currents can be obtained by solving (2-27) for $\underline{I}^*(0)$ and $\underline{I}^*(\ell)$ and using (2-26c) and (2-26d) to obtain

$$\underline{I}(0) = \underset{\sim}{T}\, \underline{I}^*(0) \tag{2-28a}$$

$$\underline{I}(\mathcal{L}) = \underset{\sim}{T}\, \underline{I}^*(\mathcal{L}) \tag{2-28b}$$

These equations are summarized in Table 3.

There are two reasons for using the equivalent representations in Table 2 and Table 3 rather than the representations in (2-20) and (2-19). First of all, note the direct similarity of the equations in Table 2 and Table 3. The only differences (other than symbols) between equations (1) and (2) in Table 2 and the corresponding equations (1) and (2) in Table 3 is that $\underset{\sim}{\Lambda}$ used in Table 2 corresponds to $\underset{\sim}{\Lambda}^{-1}$ in Table 3, and $\underline{I}^*_{\mathcal{L}}$ in Table 2 corresponds to $-\underline{V}^*_{\mathcal{L}}$ in Table 3. (Note that since $\underset{\sim}{\Lambda}$, $\underset{\sim}{\Lambda}^{-1}$ and $\underset{\sim}{E}^-$ are diagonal, $\underset{\sim}{E}^-\, \underset{\sim}{\Lambda}^{-1} = \underset{\sim}{\Lambda}^{-1}\, \underset{\sim}{E}^-$ and $\underset{\sim}{E}^-\, \underset{\sim}{\Lambda} = \underset{\sim}{\Lambda}\, \underset{\sim}{E}^-$.) Therefore we may form the Norton Equivalent equations in the programs and not need to write a duplicate set for the Thevenin Equivalent representations.

The second reason for using the representations in Table 2 and Table 3 is that if the termination networks are purely resistive, i.e., $\underset{\sim}{Z}_0$, $\underset{\sim}{Z}_{\mathcal{L}}$, $\underset{\sim}{Y}_0$ and $\underset{\sim}{Y}_{\mathcal{L}}$ are real, and the transformation matrix, $\underset{\sim}{T}$, is frequency independent, i.e., perfect conductors are assumed (as in XTALK and FLATPAK), then the matrix multiplications as well as the inversion of $\underset{\sim}{T}$ to form $\underset{\sim}{T}^{-1}$ needed to obtain $\underset{\sim}{Y}^*_0$, $\underset{\sim}{Y}^*_{\mathcal{L}}$, $\underset{\sim}{Z}^*_0$, $\underset{\sim}{Z}^*_{\mathcal{L}}$ need only be performed once and need not be changed as the frequency is changed. Only equations (1) and (2) in Table 2 and Table 3 need be reformulated for each frequency. This can represent a significant savings in computation time when the line response for many frequencies is desired (as it usually is) since n^3 operations (multiplications or divisions) are required to multiply two "full" $n \times n$ matrices which is the minimum number of operations required to obtain the inverse of a general $n \times n$ matrix [1].

TABLE 2

Programmed Equations for the Generalized

Norton Equivalent Representation

$$(1) \qquad [\underset{\sim}{Y}^{*}_{\ell} \underset{\sim}{E}^{+} + \underset{\sim}{Y}^{*}_{\ell} \underset{\sim}{\Lambda} \underset{\sim}{E}^{-} \underset{\sim}{Y}^{*}_{0} + \underset{\sim}{E}^{-} \underset{\sim}{\Lambda}^{-1} + \underset{\sim}{E}^{+} \underset{\sim}{Y}^{*}_{0}]\, \underline{V}^{*}(0)$$

$$= [\underset{\sim}{E}^{+} + \underset{\sim}{Y}^{*}_{\ell} \underset{\sim}{\Lambda} \underset{\sim}{E}^{-}]\, \underline{I}^{*}_{0} + \underline{I}^{*}_{\ell}$$

$$(2) \qquad \underline{V}^{*}(\ell) = -\underset{\sim}{\Lambda} \underset{\sim}{E}^{-} \underline{I}^{*}_{0} + [\underset{\sim}{E}^{+} + \underset{\sim}{\Lambda} \underset{\sim}{E}^{-} \underset{\sim}{Y}^{*}_{0}]\, \underline{V}^{*}(0)$$

$$(3) \qquad \underset{\sim}{T}^{-1} \underset{\sim}{Y} \underset{\sim}{Z} \underset{\sim}{T} = \underset{\sim}{T}^{-1}\{j\omega \underset{\sim}{C}[\underset{\sim}{R}_{c} + j\omega \underset{\sim}{L}_{c} + j\omega \underset{\sim}{L}]\} \underset{\sim}{T} = \underset{\sim}{\gamma}^{2}$$

$$(4) \qquad \underset{\sim}{\gamma} = j\omega \underset{\sim}{\Lambda}$$

$$(5) \qquad \underline{I}(0) = \underline{I}_{0} - \underset{\sim}{Y}_{0} \underline{V}(0) \quad , \quad \underline{I}(\ell) = -\underline{I}_{\ell} + \underset{\sim}{Y}_{\ell} \underline{V}(\ell)$$

$$(6) \qquad \underset{\sim}{Y}^{*}_{0} = \underset{\sim}{T}^{-1} \underset{\sim}{Y}_{0} \underset{\sim}{C}^{-1} \underset{\sim}{T} \quad , \quad \underset{\sim}{Y}^{*}_{\ell} = \underset{\sim}{T}^{-1} \underset{\sim}{Y}_{\ell} \underset{\sim}{C}^{-1} \underset{\sim}{T}$$

$$(7) \qquad \underline{I}^{*}_{0} = \underset{\sim}{T}^{-1} \underline{I}_{0} \quad , \quad \underline{I}^{*}_{\ell} = \underset{\sim}{T}^{-1} \underline{I}_{\ell}$$

$$(8) \qquad \underset{\sim}{E}^{+} = \frac{1}{2}\left(e^{\underset{\sim}{\gamma}\ell} + e^{-\underset{\sim}{\gamma}\ell}\right) \quad , \quad \underset{\sim}{E}^{-} = \frac{1}{2}\left(e^{\underset{\sim}{\gamma}\ell} - e^{-\underset{\sim}{\gamma}\ell}\right)$$

$$(9) \qquad \underline{V}(0) = \underset{\sim}{C}^{-1} \underset{\sim}{T} \underline{V}^{*}(0) \quad , \quad \underline{V}(\ell) = \underset{\sim}{C}^{-1} \underset{\sim}{T} \underline{V}^{*}(\ell)$$

TABLE 3

Programmed Equations for the Generalized Thevenin Equivalent Representation

(1) $$[\tilde{Z}^*_\ell \tilde{E}^+ + \tilde{Z}^*_\ell \tilde{E}^- \tilde{\Lambda}^{-1} \tilde{Z}^*_0 + \tilde{\Lambda} \tilde{E}^- + \tilde{E}^+ \tilde{Z}^*_0]\, \underline{I}^*(0) = [\tilde{E}^+ + \tilde{Z}^*_\ell \tilde{E}^- \tilde{\Lambda}^{-1}]\, \underline{V}^*_0 - \underline{V}^*_\ell$$

(2) $$\underline{I}^*(\ell) = -\tilde{E}^- \tilde{\Lambda}^{-1} \underline{V}^*_0 + [\tilde{E}^+ + \tilde{E}^- \tilde{\Lambda}^{-1} \tilde{Z}^*_0]\, \underline{I}^*(0)$$

(3) $$\tilde{T}^{-1} \tilde{Y} \tilde{Z} \tilde{T} = \tilde{T}^{-1} \{j\omega \tilde{C}[\tilde{R}_c + j\omega \tilde{L}_c + j\omega \tilde{L}]\} \tilde{T} = \tilde{\gamma}^2$$

(4) $$\tilde{\gamma} = j\omega \tilde{\Lambda}$$

(5) $$\underline{V}(0) = \underline{V}_0 - \tilde{Z}_0 \underline{I}(0) \quad , \quad \underline{V}(\ell) = \underline{V}_\ell + \tilde{Z}_\ell \underline{I}(\ell)$$

(6) $$\tilde{Z}^*_0 = \tilde{T}^{-1} \tilde{C} \tilde{Z}_0 \tilde{T} \quad , \quad \tilde{Z}^*_\ell = \tilde{T}^{-1} \tilde{C} \tilde{Z}_\ell \tilde{T}$$

(7) $$\underline{V}^*_0 = \tilde{T}^{-1} \tilde{C} \underline{V}_0 \quad , \quad \underline{V}^*_\ell = \tilde{T}^{-1} \tilde{C} \underline{V}_\ell$$

(8) $$\tilde{E}^+ = \frac{1}{2}(e^{\tilde{\gamma}\ell} + e^{-\tilde{\gamma}\ell}) \quad , \quad \tilde{E}^- = \frac{1}{2}(e^{\tilde{\gamma}\ell} - e^{-\tilde{\gamma}\ell})$$

(9) $$\underline{I}(0) = \tilde{T}\, \underline{I}^*(0) \quad , \quad \underline{I}(\ell) = \tilde{T}\, \underline{I}^*(\ell)$$

Note: $$\underline{V}^*(0) = \underline{V}^*_0 - \tilde{Z}^*_0 \underline{I}^*(0) \quad , \quad \underline{V}^*(\ell) = \underline{V}^*_\ell + \tilde{Z}^*_\ell \underline{I}^*(\ell)$$

where: $$\underline{V}^*(0) = \tilde{T}^{-1} \tilde{C}\, \underline{V}(0) \quad , \quad \underline{V}^*(\ell) = \tilde{T}^{-1} \tilde{C}\, \underline{V}(\ell)$$

2.3 Formulation of the Terminal Network Equations

The previous formulation requires that one determine the entries in the $n \times n$ matrices $\underset{\sim}{Z}_0$, $\underset{\sim}{Z}_{\mathcal{L}}$, $\underset{\sim}{Y}_0$ and $\underset{\sim}{Y}_{\mathcal{L}}$, and the $n \times 1$ vectors, $\underline{V}_0$, $\underline{V}_{\mathcal{L}}$, $\underline{I}_0$ and $\underline{I}_{\mathcal{L}}$, in the Thevenin and Norton Equivalent representations of the terminal networks in (2-12) and (2-13), respectively. In this section, some examples will be given to aid in determining these quantities.

To illustrate this, four examples will be used. The first example, Example 1, is shown in Figure 2-4a. In this example, there is no cross-coupling between the port terminals within the termination networks, i.e., at each end of the line, each endpoint of a wire is terminated directly to the reference conductor and is not physically connected to the endpoints of other wires at the same end of the line. Writing the following equations:

$$V_1(0) = 1 - 1\ I_1\ (0) \tag{2-29a}$$

$$V_2(0) = -10\ I_2\ (0) \tag{2-29b}$$

$$V_1(\mathcal{L}) = 10^3\ I_1\ (\mathcal{L}) \tag{2-29c}$$

$$V_2(\mathcal{L}) = 10^4\ I_2\ (\mathcal{L}) + 1 \tag{2-29d}$$

and comparing these equations to the Thevenin Equivalent representation

$$\underline{V}(0) = \underline{V}_0 - \underset{\sim}{Z}_0\ \underline{I}(0) \tag{2-30a}$$

$$\underline{V}(\mathcal{L}) = \underline{V}_{\mathcal{L}} + \underset{\sim}{Z}_{\mathcal{L}}\ \underline{I}(\mathcal{L}) \tag{2-30b}$$

where

$$\underline{V}(0) = \begin{bmatrix} V_1(0) \\ V_2(0) \end{bmatrix} \qquad \underline{V}(\mathcal{L}) = \begin{bmatrix} V_1(\mathcal{L}) \\ V_2(\mathcal{L}) \end{bmatrix}$$
$$\underline{I}(0) = \begin{bmatrix} I_1(0) \\ I_2(0) \end{bmatrix} \qquad \underline{I}(\mathcal{L}) = \begin{bmatrix} I_1(\mathcal{L}) \\ I_2(\mathcal{L}) \end{bmatrix} \tag{2-31}$$

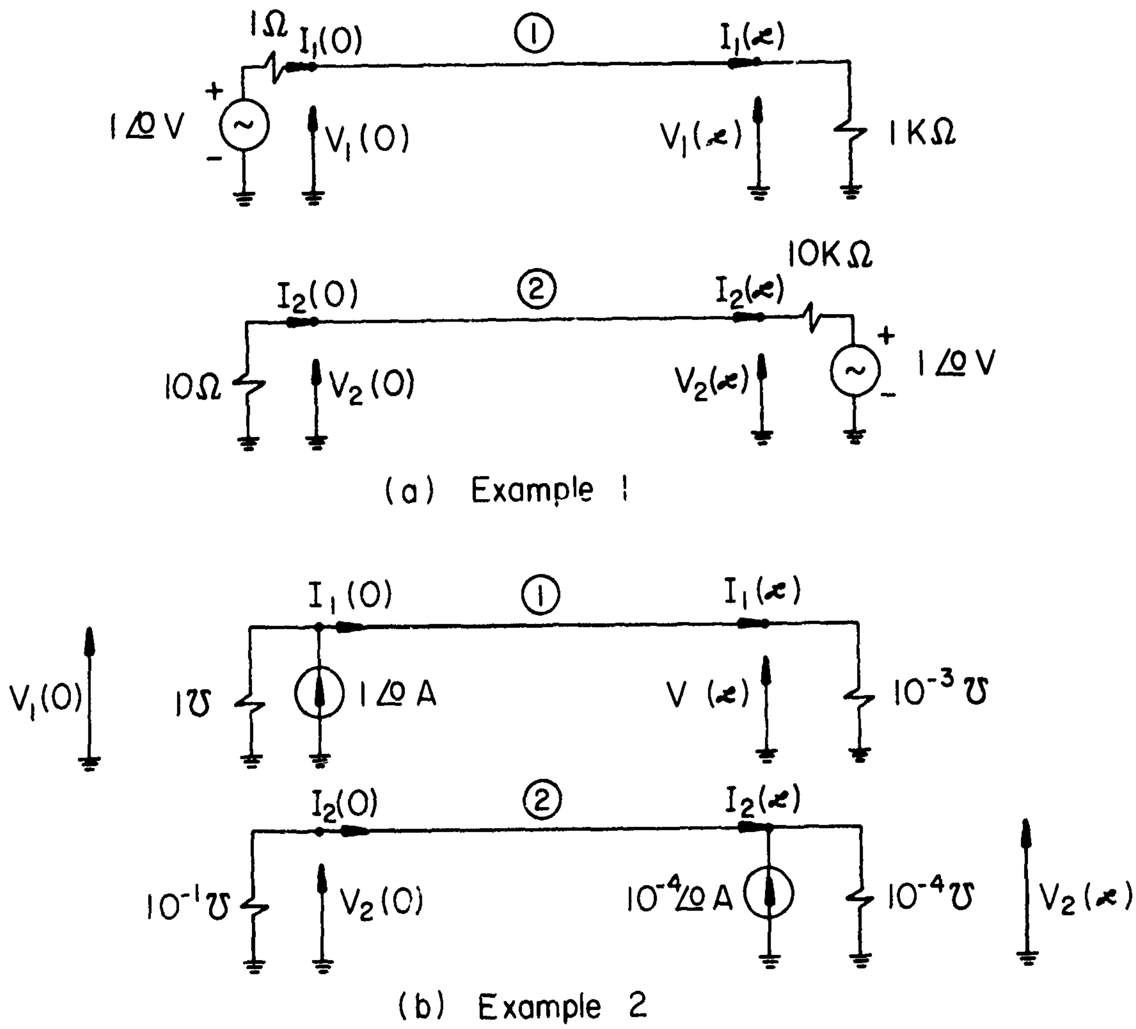


Fig. 2-4. Example termination networks. (No cross-coupling)

one can readily identify

$$\underline{V}_0 = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \qquad \underset{\sim}{Z}_0 = \begin{bmatrix} 1 & 0 \\ 0 & 10 \end{bmatrix}$$

$$\underline{V}_\ell = \begin{bmatrix} 0 \\ 1 \end{bmatrix} \qquad \underset{\sim}{Z}_\ell = \begin{bmatrix} 10^3 & 0 \\ 0 & 10^4 \end{bmatrix} \tag{2-32}$$

Similarly, one can convert the termination networks to a Norton equivalent representation in Figure 2-4b and obtain (Example 2)

$$I_2(0) = 1 - 1\ V_1(0) \tag{2-33a}$$

$$I_2(0) = -10^{-1}\ V_2(0) \tag{2-33b}$$

$$I_1(\ell) = 10^{-3}\ V_1(\ell) \tag{2-33c}$$

$$I_2(\ell) = -10^{-4} + 10^{-4}\ V_2(\ell) \tag{2-33d}$$

Comparing these equations to the Norton Equivalent representation

$$\underline{I}(0) = \underline{I}_0 - \underset{\sim}{Y}_0\ \underline{V}(0) \tag{2-34a}$$

$$\underline{I}(\ell) = -\underline{I}_\ell + \underset{\sim}{Y}_\ell\ \underline{V}(\ell) \tag{2-34b}$$

where $\underline{I}(0)$, $\underline{I}(\ell)$, $\underline{V}(0)$, $\underline{V}(\ell)$ are given in (2-31), one can readily identify for Example 2

$$\underline{I}_0 = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \qquad \underset{\sim}{Y}_0 = \begin{bmatrix} 1 & 0 \\ 0 & 10^{-1} \end{bmatrix}$$

$$\underline{I}_\ell = \begin{bmatrix} 0 \\ 10^{-4} \end{bmatrix} \qquad \underset{\sim}{Y}_\ell = \begin{bmatrix} 10^{-3} & 0 \\ 0 & 10^{-4} \end{bmatrix} \tag{2-35}$$

Note that

$$\underline{I}_0 = \underset{\sim}{Z}_0^{-1}\ \underline{V}_0 \tag{2-36a}$$

$$\underset{\sim}{Y}_0 = \underset{\sim}{Z}_0^{-1} \tag{2-36b}$$

$$\underline{I}_\ell = \underset{\sim}{Z}_\ell^{-1}\, \underline{V}_\ell \tag{2-36c}$$

$$\underset{\sim}{Y}_\ell = \underset{\sim}{Z}_\ell^{-1} \tag{2-36d}$$

Note also that as far as the network terminal characteristics are concerned, the termination networks in Figure 2-4a are the same as those in Figure 2-4b.

The third and fourth examples, Example 3 and Example 4, are shown in Figure 2-5. As far as terminal characteristics are concerned, the terminations in Figure 2-5a and in Figure 2-5b are the same as shown by the following. First,write the Norton Equivalent characterization for the terminations in Figure 2-5b as (treat the terminal currents as independent sources and write the node-voltage circuit equations of the networks)

$$\underbrace{\begin{bmatrix} I_1(0) \\ I_2(0) \end{bmatrix}}_{\underline{I}(0)} = \underbrace{\begin{bmatrix} 1 \\ 0 \end{bmatrix}}_{\underline{I}_0} - \underbrace{\begin{bmatrix} .6 & -.4 \\ -.4 & .6 \end{bmatrix}}_{\underset{\sim}{Y}_0} \underbrace{\begin{bmatrix} V_1(0) \\ V_2(0) \end{bmatrix}}_{\underline{V}_0} \tag{2-37a}$$

$$\underbrace{\begin{bmatrix} I_1(\ell) \\ I_2(\ell) \end{bmatrix}}_{\underline{I}(\ell)} = \underbrace{\begin{bmatrix} 0 \\ 1 \end{bmatrix}}_{\underline{I}_\ell} + \underbrace{\begin{bmatrix} .6 & -.2 \\ -.2 & .4 \end{bmatrix}}_{\underset{\sim}{Y}_\ell} \underbrace{\begin{bmatrix} V_1(\ell) \\ V_2(\ell) \end{bmatrix}}_{\underline{V}_\ell} \tag{2-37b}$$

Similarly, from Figure 2-5a write the Thevenin Equivalent characterization as (treat the terminal voltages as independent sources and write the loop current circuit equations of the networks)

$$\underbrace{\begin{bmatrix} V_1(0) \\ V_2(0) \end{bmatrix}}_{\underline{V}(0)} = \underbrace{\begin{bmatrix} 3 \\ 2 \end{bmatrix}}_{\underline{V}_0} - \underbrace{\begin{bmatrix} 3 & 2 \\ 2 & 3 \end{bmatrix}}_{\underset{\sim}{Z}_0} \underbrace{\begin{bmatrix} I_1(0) \\ I_2(0) \end{bmatrix}}_{\underline{I}(0)} \tag{2-38a}$$

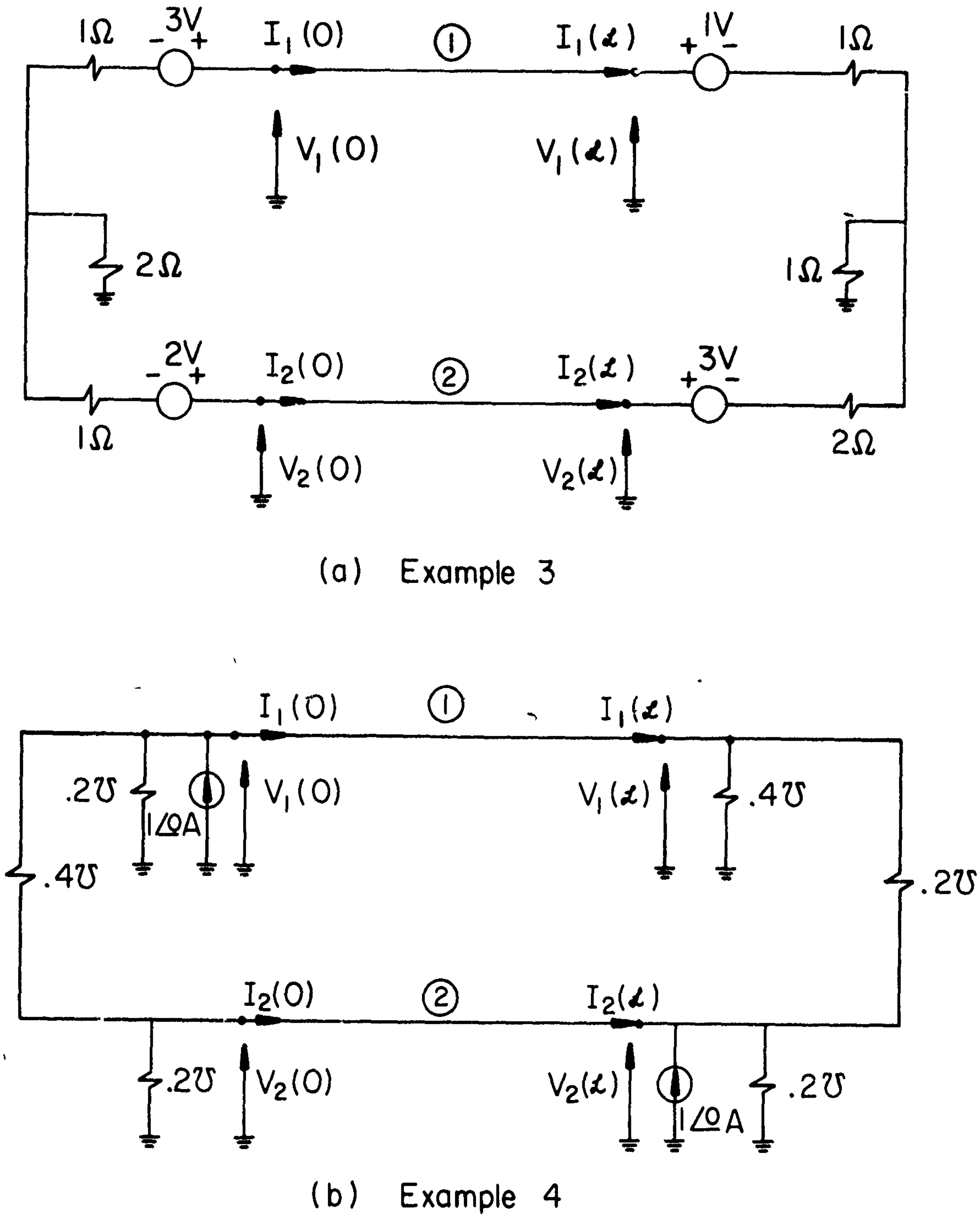


Fig. 2-5. Example termination networks. (cross-coupling)

$$\underbrace{\begin{bmatrix} V_1(\ell) \\ V_2(\ell) \end{bmatrix}}_{\underline{V}(\ell)} = \underbrace{\begin{bmatrix} 1 \\ 3 \end{bmatrix}}_{\underline{V}_{\ell}} + \underbrace{\begin{bmatrix} 2 & 1 \\ 1 & 3 \end{bmatrix}}_{\tilde{Z}_{\ell}} \underbrace{\begin{bmatrix} I_1(\ell) \\ I_2(\ell) \end{bmatrix}}_{\underline{I}(\ell)} \qquad (2\text{-}38b)$$

Note that

$$\tilde{Y}_0 = \tilde{Z}_0^{-1} \qquad (2\text{-}39a)$$

$$\tilde{Y}_{\ell} = \tilde{Z}_{\ell}^{-1} \qquad (2\text{-}39b)$$

$$\underline{I}_0 = \tilde{Y}_0 \underline{V}_0 \qquad (2\text{-}39c)$$

$$\underline{I}_{\ell} = \tilde{Y}_{\ell} \underline{V}_{\ell} \qquad (2\text{-}39d)$$

and as far as the terminal characteristics of the networks are concerned, the termination networks in Figure 2-5a are the same as those in Figure 2-5b.

The above examples will serve a dual purpose. Each of the computer programs will be run for each of the above four examples for the same transmission line structure. Typical solution printouts will be shown for these results. This will serve as a partial check on the proper functioning of the programs since the corresponding terminal voltages ($V_1(0)$, $V_2(0)$, $V_1(\ell)$, $V_2(\ell)$) for Example 1 should equal those for Example 2. Similarly the corresponding terminal voltages for Example 3 should equal those for Example 4.

As can be seen from the above examples, if there is no cross-coupling within the termination networks, then formulation of the entries in $\underline{V}_0$, $\underline{V}_{\ell}$, $\tilde{Z}_0$ and $\tilde{Z}_{\ell}$ or $\underline{I}_0$, $\underline{I}_{\ell}$, $\tilde{Y}_0$ and $\tilde{Y}_{\ell}$ is particularly simple. The situation in which there is no cross-coupling within the termination networks is generally the problem of interest in wire-coupled interference calculations.

However, it was felt that the more general case of allowing cross-coupling within the terminal networks be included in the capabilities of the programs.

To save computer time, one has four options for inputting the terminal data: OPTIONS 11, 12, 21, or 22. The first digit in each number indicates to each program that the terminal characterization chosen is either the Thevenin Equivalent (1) or Norton Equivalent (2). The second digit indicates to the program whether the admittance ($\underset{\sim}{Y}_0$ and $\underset{\sim}{Y}_\ell$) or impedance ($\underset{\sim}{Z}_0$ and $\underset{\sim}{Z}_\ell$) matrices are diagonal (1), i.e., no cross-coupling, or full (2), i.e., cross-coupling. For example, OPTION 11 indicates Thevenin Equivalent, diagonal impedance matrices; OPTION 22 indicates Norton Equivalent, full admittance matrices; OPTION 12 indicates Thevenin Equivalent, full impedance matrices, and OPTION 21 indicates Norton Equivalent, diagonal admittance matrices.

This saves computer time and user effort in inputting the data. For example, in cases where $\underset{\sim}{Z}_0$(or $\underset{\sim}{Z}_\ell$, or $\underset{\sim}{Y}_0$ or $\underset{\sim}{Y}_\ell$) must be multiplied by another $n \times n$ matrix such as in $\underset{\sim}{T}\,\underset{\sim}{Z}_0$, if $\underset{\sim}{Z}_0$ is diagonal one only needs n^2 multiplications to form this product whereas if $\underset{\sim}{Z}_0$ is full, n^3 multiplications are needed to form the product. The programs are written to take advantage of this. In addition, if the terminal admittance or impedance matrices are in fact diagonal, then the user need only input the entries on the main diagonal and is saved the drudgery of inputting the remaining zero entries. The specific details for inputting this termination network data will be given in Chapter IV, the User's Manual.

2.4 Common Impedance Coupling and the Calculation of Conductor Self Impedances

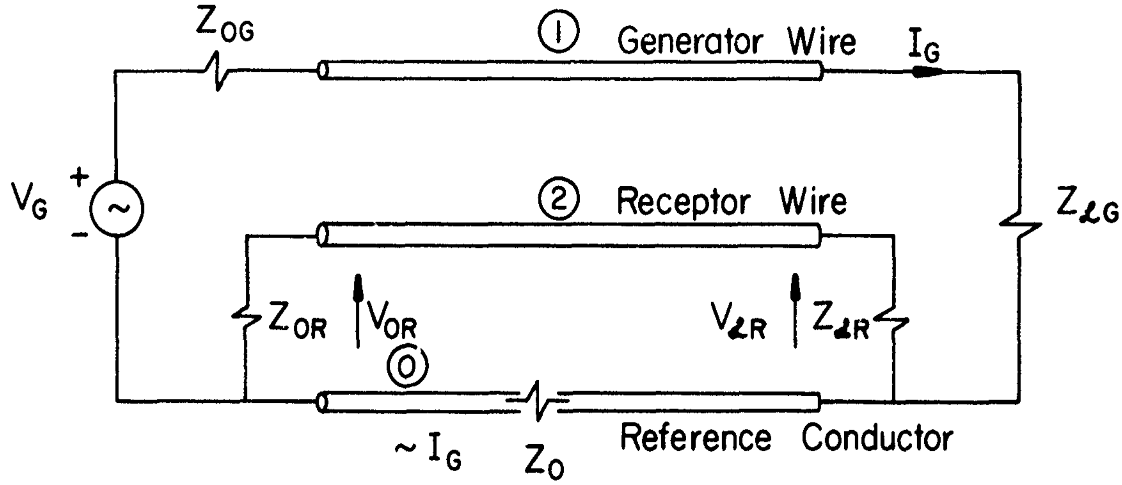
Programs XTALK and FLATPAK assume that all conductors are perfect conductors. Programs XTALK2 and FLATPAK2, however, do not assume perfect conductors and these programs include the per-unit-length conductor resistance and internal inductance, the items r_{c_i} and ℓ_{c_i}, respectively, in Figure 2-2 and (2-5) as well as the reference conductor resistance, r_{c_0}, and

inductance, ℓ_{c_0}.

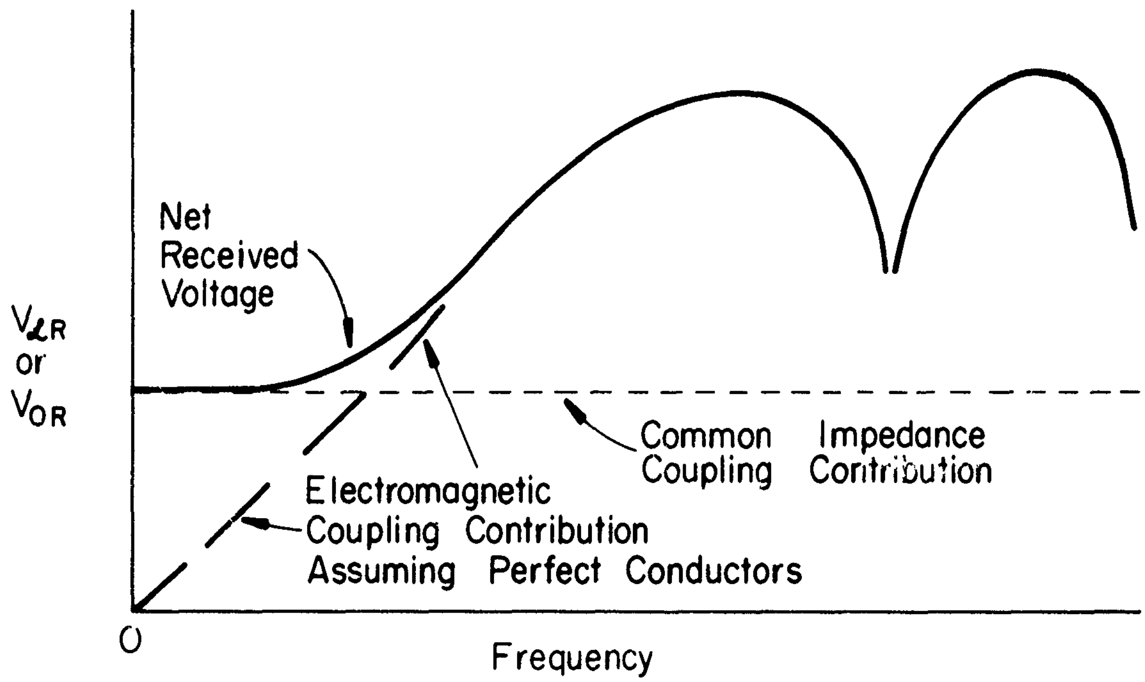
The reason for writing two separate programs to consider the same transmission line structure such as XTALK and XTALK2 is that the inclusion of conductor losses in the transmission line solution requires a longer computer run time and more array storage than when perfect conductors are assumed. This can be seen in Tables 2 and 3 in that the transformation matrix $\tilde{T}$ will be frequency dependent (and complex) when losses are included, whereas $\tilde{T}$ will be frequency independent (and real) when perfect conductors are assumed, i.e., $\tilde{R}_c = \tilde{L}_c = \tilde{0}_{n,n}$. Therefore when perfect conductors are assumed (in XTALK and FLATPAK), one need only compute $\tilde{T}$ once per problem and the same $\tilde{T}$ can be used throughout the frequency iteration. When lossy conductors are considered (in XTALK2 and FLATPAK2), one must recompute $\tilde{T}$ at each frequency in addition to reforming at each frequency those matrix products involving $\tilde{T}$ in Table 2 and Table 3.

The primary effect of imperfect conductors is to introduce common impedance coupling. Consider a transmission line in which there is no cross-coupling within the termination networks. In this case, clearly the voltages induced via electromagnetic field coupling at the ends of a "receptor" circuit consisting of one conductor (wire) and the reference conductor due to a "generator" circuit consisting of another wire and the reference conductor will approach zero as the frequency of excitation is reduced to zero. However, the reference conductor impedance can couple a signal into the receptor circuit even at D-C and this is usually termed common impedance coupling.

To illustrate this, consider Figure 2-6. In Figure 2-6a, a three-conductor transmission line is shown. The reference conductor has a certain total impedance, Z_0, which may be considerably smaller in magnitude than



(a)



(b)

Fig. 2-6. Illustration of common impedance coupling.

Z_{0R} or $Z_{\ell R}$. Consequently, the current in the generator wire at frequencies approaching D-C may be determined as

$$I_G \cong \frac{V_G}{Z_{0G} + Z_{\ell G}} \tag{2-40}$$

The major portion of this current will pass through the reference conductor producing a voltage drop across Z_0. This results in received voltages

$$V_{\ell R} \cong -\left[\frac{Z_{\ell R}}{Z_{\ell R} + Z_{0R}}\right] Z_0 \, I_G \tag{2-41a}$$

$$V_{0R} \cong \left[\frac{Z_{0R}}{Z_{\ell R} + Z_{0R}}\right] Z_0 \, I_G \tag{2-41b}$$

Although this portion of the total received voltage may be "small" it may nevertheless be larger than the contribution due to electromagnetic field coupling as shown in Figure 2-6b. Consequently, this common impedance coupling generates a "floor" of induced voltage where a solution assuming perfect conductors would indicate a perhaps negligably small received voltage at the lower frequencies.

The frequency at which this common impedance coupling becomes significant depends on many factors some of which are line geometry (which affects the level of the electromagnetic portion of the coupling) and type of reference conductor. Reference conductors consisting of a #36 gauge wire or a large, thick ground plane would certainly not produce the same level of common impedance coupling.

The above separation and superposition of the two coupling mechanisms is only correct when one dominates the other by a considerable amount. To obtain a quantitatively correct answer, one must include the conductor self impedances directly in the transmission line solution and this is done in

XTALK2 and FLATPAK2.

The transmission lines considered by all programs in this report consist of n wires (cylindrical conductors) and a reference conductor. In XTALK2, there are three choices for the reference conductor; (1) a wire, (2) a finite ground plane and (3) an overall cylindrical shield surrounding the n wires. When the reference conductor is a finite ground plane, the user simply inputs the per-unit-length resistance and self inductance of the ground plane. Thus there are two cases remaining to be considered.

The per-unit-length self impedance of a solid cylinder of radius r_w shown in Figure 2-7a is given by the following. Define

$$\delta = \frac{1}{\sqrt{\pi f \mu_v \sigma}} = \frac{1}{2\pi \sqrt{\sigma f \times 10^{-7}}} \tag{2-42a}$$

$$r_0 = \frac{1}{\pi\sigma r_w^2} \tag{2-42b}$$

$$\ell_0 = \frac{\mu_v}{8\pi} = .5 \times 10^{-7} \tag{2-42c}$$

where σ is the conductor conductivity, f is the frequency and μ_v is the permeability of the metal which is assumed to be that of free space ($\mu_v = 4\pi \times 10^{-7}$). The quantity δ is the conventional skin depth factor. The equations for the per-unit-length self impedance of a solid cylindrical conductor including skin effect are obtained from [6]. The equations used in the computer programs approximate the actual equations given in reference [6], pp. 78-80. The programmed equations are

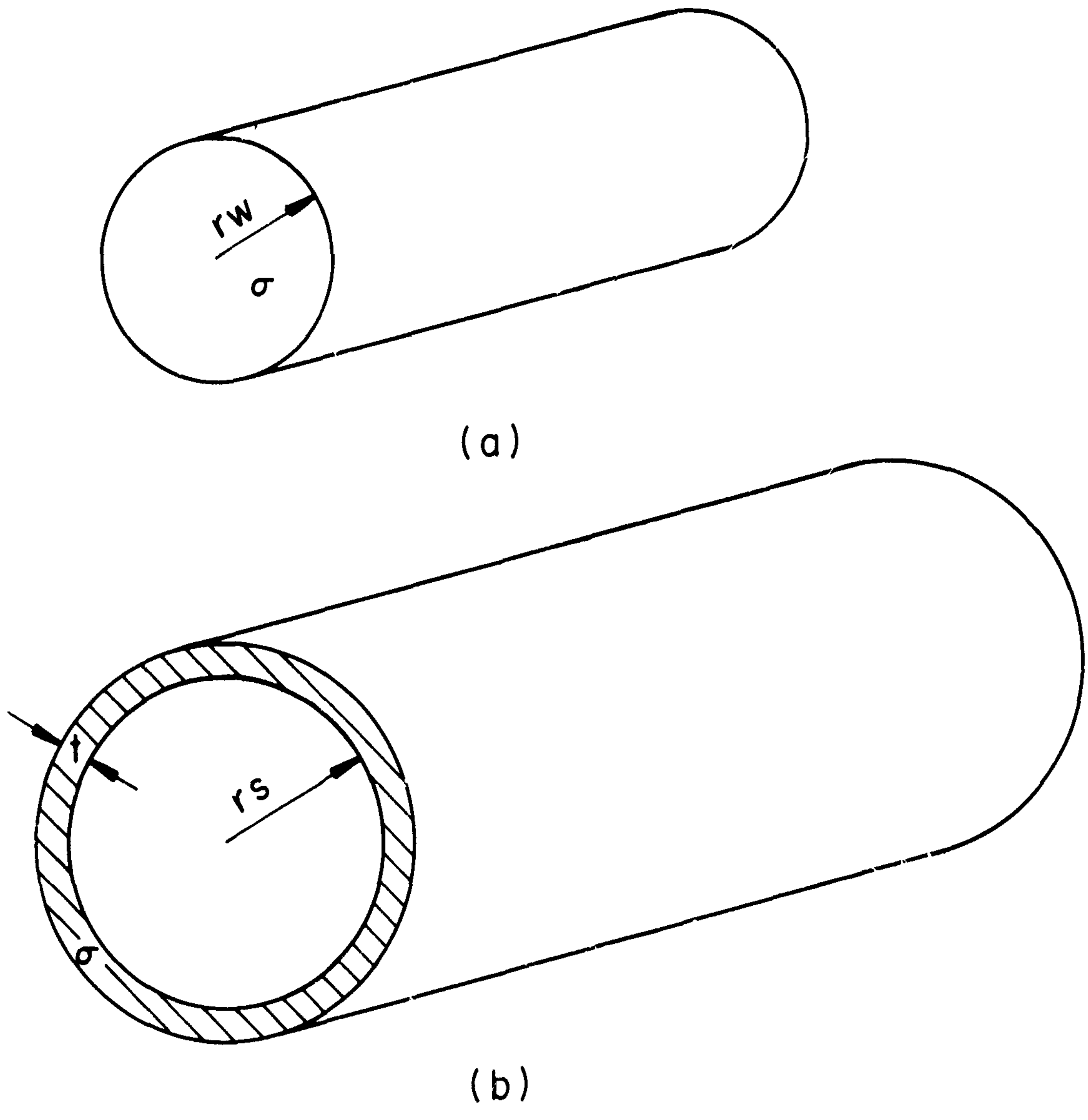


Fig. 2-7. Conductor dimensions for calculating common impedance.

(I) $r_w \leq \delta$

$$r = r_0 \quad \text{ohms/meter} \tag{2-43a}$$

$$\ell = \ell_0 \quad \text{henrys/meter} \tag{2-43b}$$

(II) $\delta < r_w < 3\delta$

$$r = \frac{1}{4}\left(\frac{r_w}{\delta} + 3\right) r_0 \quad \text{ohms/meter} \tag{2-44a}$$

$$\ell = \left[1.15 - .15 \left(\frac{r_w}{\delta}\right)\right] \ell_o \quad \text{henrys/meter} \tag{2-44b}$$

(III) $r_w \geq 3\delta$

$$r = \frac{r_w}{2\delta}\ r_0 \quad \text{ohms/meter} \tag{2-45a}$$

$$\ell = \frac{2\delta}{r_w}\ \ell_0 \quad \text{henrys/meter} \tag{2-45b}$$

These equations are used to generate the per-unit-length self impedances of the transmission line wires ($z_i = r+j\omega\ell$) and the reference conductor when the reference conductor is also a wire ($z_0 = r+j\omega\ell$). They are stored within the program codes for XTALK2 and FLATPAK2 and the user needs to input only the physical dimensions of the wires and their conductivity.

For the purposes of computing these wire self impedances, the wires are considered to be stranded. The user inputs the radius of each strand (in mils) and the number of strands in each wire. The program then computes the per-unit-length self impedance of each strand and determines the net wire self impedance by dividing this result by the number of strands (the net resistance of the wire is considered to be the result of all strands of the wire in parallel). (All strands in a wire are considered to be identical)

The equations for the per-unit-length self impedance of the reference conductor when the reference conductor is a thin walled,overall, cylindrical

shield shown in Figure 2-7b are taken from reference [7], pp. 301-303 and include skin effect. The equations used in the computer programs are approximations of the actual equations. The skin depth, δ, is given in (2-42a). Denote the interior radius of the cylinder by r_s and its wall thickness by t. The equations become [7]

$$r_0 = \frac{1}{\pi\sigma t(2r_s+t)} \tag{2-46}$$

(I) $t \leq .5\delta$

$$r = r_0 \quad \text{ohms/meter} \tag{2-47a}$$

$$\omega\ell = .4(\frac{t}{\delta})\, r_0 \quad \text{ohms/meter} \tag{2-47b}$$

(II) $t \geq 3\delta$

$$r = \frac{1}{2\pi r_s \sigma\delta} \quad \text{ohms/meter} \tag{2-48a}$$

$$\omega\ell = r \quad \text{ohms/meter} \tag{2-48b}$$

(III) $.5\delta < t < 3\delta$

$$r = \frac{1}{2\pi r_s \sigma\delta}\left[\frac{\sinh(\frac{2t}{\delta}) + \sin(\frac{2t}{\delta})}{\cosh(\frac{2t}{\delta}) - \cos(\frac{2t}{\delta})}\right] \quad \text{ohms/meter} \tag{2-49a}$$

$$\omega\ell = \frac{1}{2\pi r_s \sigma\delta}\left[\frac{\sinh(\frac{2t}{\delta}) - \sin(\frac{2t}{\delta})}{\cosh(\frac{2t}{\delta}) - \cos(\frac{2t}{\delta})}\right] \quad \text{ohms/meter} \tag{2-49b}$$

The per-unit-length self impedance of the shield is given by $z_0 = r+j\omega\ell$. These equations are stored in the XTALK2 program code. The user only needs to input the shield interior radius, the shield thickness and the conductivity of the shield.

2.5 Computation of the Per-Unit-Length Inductance and Capacitance Matrices

All of the formulations shown in Tables 2 and 3 require the computation of the nxn, real, symmetric, per-unit-length transmission line inductance and capacitance matrices, $\underset{\sim}{L}$ and $\underset{\sim}{C}$, respectively. The computation of these matrices will be discussed in this section.

2.5.1 Transmission Lines Consisting of Perfect Conductors in a Lossless, Homogeneous Medium, XTALK

This section considers (n+1) conductor transmission lines consisting of (n+1) perfect conductors in a lossless, homogeneous medium. The lines consist of n wires and three choices of reference conductor (the zero-th conductor) cross sections of which are shown in Figure 2-8. Computer program XTALK considers these cases.

The per-unit-length inductance and capacitance matrices for lines in a homogeneous medium are related by [1]

$$\underset{\sim}{L}\,\underset{\sim}{C} = \mu\varepsilon \underset{\sim}{1}_n \tag{2-50}$$

where μ and ε are the permeability and permittivity of the surrounding homogeneous medium. The per-unit-length capacitance matrix can be found from a knowledge of the per-unit-length inductance matrix from (2-50) as

$$\underset{\sim}{C} = \mu\varepsilon \underset{\sim}{L}^{-1} \tag{2-51}$$

A logical choice for the surrounding medium in Figure 2-8(a) and 2-8(b) would be free space with permeability $\mu_v = 4\pi x 10^{-7}$ henrys/meter and permittivity $\varepsilon_v \cong (1/36\pi)x10^{-9}$ farads/meter. However, for all structure types, the homogeneous medium may be characterized, for generality, by a relative dielectric constant (permittivity) of ε_r and a relative permeability of μ_r. (Although the permeability of typical dielectrics is that of free space, μ_v,

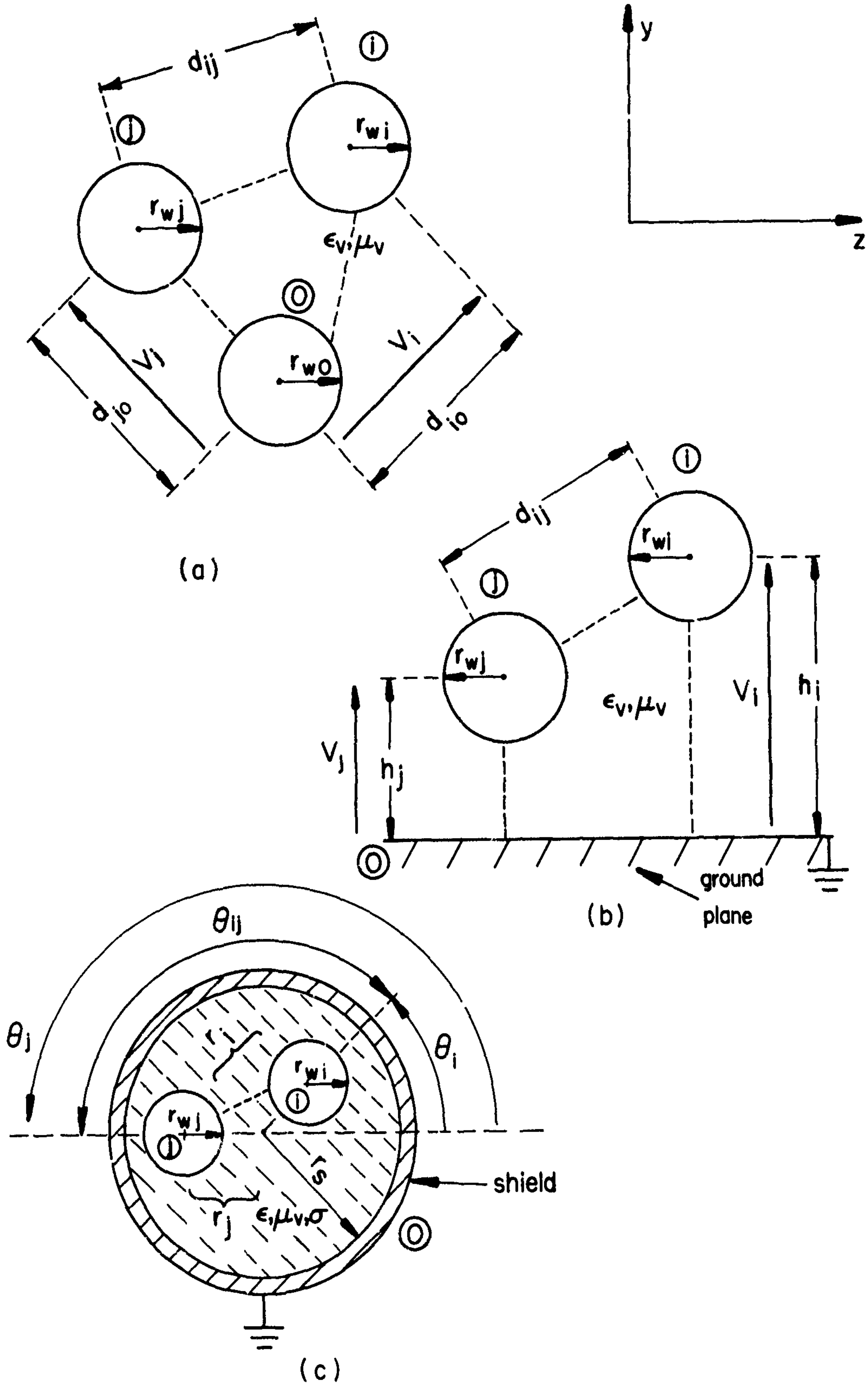


Fig. 2-8. Lines in a homogeneous medium.

the programs XTALK and XTALK2 allow for the more general case.)

For the case of lossless conductors in a lossless, homogeneous medium, the nχn characteristic impedance matrix, $\underset{\sim}{Z}_C$, in (2-11) is related to the per-unit-length inductance matrix by [1]

$$\underset{\sim}{Z}_C = \nu \underset{\sim}{L} = \frac{\nu_o}{\sqrt{\varepsilon_r \mu_r}} \underset{\sim}{L} \tag{2-52}$$

where $\nu = 1/\sqrt{\mu\varepsilon}$ is the velocity of light in the surrounding medium. The velocity of light in free space, ν_o, to 7 digits is 2.997925 x 10^8 meters/second.

The equations used in the programs for the entries in the per-unit-length transmission line matrix are derived in Volume I of this series [1] and are valid for "large" conductor separations. Generally this means that the smallest ratio of wire separation to wire radius should be no smaller than approximately 5. A more complete discussion of this is found in Volume I.

When the reference conductor is a wire as shown in Figure 2-8(a), the entries in the per-unit-length transmission line matrix are given by [1]

$$[\underset{\sim}{L}]_{ii} = \frac{\mu_v \mu_r}{2\pi} \ell n \left(\frac{d_{i0}^2}{r_{wi} r_{w0}} \right) \tag{2-53a}$$

$$[\underset{\sim}{L}]_{ij} = \frac{\mu_v \mu_r}{2\pi} \ell n \left(\frac{d_{i0} d_{j0}}{r_{w0} d_{ij}} \right) \tag{2-53b}$$

for i, j=1, ---, n and $i \neq j$ where d_{i0} is the center-to-center separation between the i-th wire and the reference conductor, d_{ij} is the center-to-center separation between the i-th and j-th wires, and r_{wi} and r_{w0} are the radii of the i-th and reference wires, respectively.

When the reference conductor is an infinite ground plane as shown in Figure 2-8(b), the entries in the per-unit-length inductance matrix are

given by [1]

$$[\underset{\sim}{L}]_{ii} = \frac{\mu_v \mu_r}{2\pi} \ell n \left(\frac{2h_i}{r_{wi}}\right) \tag{2-54a}$$

$$[\underset{\sim}{L}]_{ij} = \frac{\mu_v \mu_r}{2\pi} \ell n \left(\frac{\sqrt{d_{ij}^2 + 4 h_i h_j}}{d_{ij}}\right) \tag{2-54b}$$

for i, j=1, ..., n and i ≠ j where h_i is the height of the i-th wire above the ground plane.

When the reference conductor is an overall cylindrical shield as shown in Figure 2-8(c), the entries in the per-unit-length inductance matrix are given by [1]

$$[\underset{\sim}{L}]_{ii} = \frac{\mu_v \mu_r}{2\pi} \ell n \left(\frac{r_s^2 - r_i^2}{r_s\, r_{wi}}\right) \tag{2-55a}$$

$$[\underset{\sim}{L}]_{ij} = \frac{\mu_v \mu_r}{2\pi} \ell n \left\{ \left(\frac{r_j}{r_s}\right) \sqrt{\frac{(r_i r_j)^2 + r_s^4 - 2r_i r_j r_s^2 \cos \Theta_{ij}}{(r_i r_j)^2 + r_j^4 - 2r_i r_j^3 \cos \Theta_{ij}}} \right\} \tag{2-55b}$$

for i, j=1, ..., n and i ≠ j where r_s is the interior radius of the shield, r_i is the separation of the i-th wire from the center of the shield and Θ_{ij} is the angular separation between the i-th and j-th wires

For the case of lossless conductors in a lossless, homogeneous medium, the equations for the terminal voltages and currents in Table 2 and Table 3 can be further simplified. Obviously, the transformation matrix, $\underset{\sim}{T}$, which diagonalizes the matrix product $\underset{\sim}{Y}\,\underset{\sim}{Z}$ can be taken to be simply the identity matrix, i.e., $\underset{\sim}{T} = \underset{\sim}{1}_n$, as is clear from the fact that for this case $\underset{\sim}{Z} = j\omega\underset{\sim}{L}$, $\underset{\sim}{Y} = j\omega\underset{\sim}{C}$ and

$$\begin{aligned} \underset{\sim}{Y}\,\underset{\sim}{Z} &= -\omega^2\, \underset{\sim}{L}\,\underset{\sim}{C} \\ &= \frac{-\omega^2}{v^2}\, \underset{\sim}{1}_n \end{aligned} \tag{2-56}$$

Also, the $n \chi n$ diagonal matrix, $\underset{\sim}{\Lambda}$, in Tables 2 and 3 becomes

$$\underset{\sim}{\Lambda} = \frac{1}{\nu} \underset{\sim}{1}_n \tag{2-57}$$

Therefore the equations for the terminal voltages, $\underline{V}(0)$ and $\underline{V}(\mathcal{L})$, for the Norton Equivalent representation of the terminal networks in Table 2 simplify to [1] (see equations (2-19) and (2-20)).

$$\begin{aligned}&[\cos(\beta\mathcal{L}) \{\underset{\sim}{Y}_{\mathcal{L}} + \underset{\sim}{Y}_0\} + j \sin(\beta\mathcal{L}) \{\underset{\sim}{Y}_{\mathcal{L}} \underset{\sim}{Z}_C \underset{\sim}{Y}_0 + \underset{\sim}{Z}_C^{-1}\}] \underline{V}(0) \\ &\quad = [\cos(\beta\mathcal{L}) \underset{\sim}{1}_n + j \sin(\beta\mathcal{L}) \underset{\sim}{Y}_{\mathcal{L}} \underset{\sim}{Z}_C] \underline{I}_0 + \underline{I}_{\mathcal{L}}\end{aligned} \tag{2-58a}$$

$$\underline{V}(\mathcal{L}) = -j \sin(\beta\mathcal{L}) \underset{\sim}{Z}_C \underline{I}_0 + [\cos(\beta\mathcal{L})\underset{\sim}{1}_n + j \sin(\beta\mathcal{L}) \underset{\sim}{Z}_C \underset{\sim}{Y}_0] \underline{V}(0) \tag{2-58b}$$

where β is the phase constant

$$\beta = \omega/\nu \tag{2-59}$$

and the characteristic impedance matrix $\underset{\sim}{Z}_C$ is given in (2-52).

Similarly the equations for the terminal currents, $\underline{I}(0)$ and $\underline{I}(\mathcal{L})$, for the Thevenin Equivalent representation in Table 3 simplify to

$$\begin{aligned}&[\cos(\beta\mathcal{L}) \{\underset{\sim}{Z}_{\mathcal{L}} + \underset{\sim}{Z}_0\} + j \sin(\beta\mathcal{L}) \{\underset{\sim}{Z}_{\mathcal{L}} \underset{\sim}{Z}_C^{-1} \underset{\sim}{Z}_0 + \underset{\sim}{Z}_C\}] \underline{I}(0) \\ &\quad = -\underline{V}_{\mathcal{L}} + [\cos(\beta\mathcal{L}) \underset{\sim}{1}_n + j \sin(\beta\mathcal{L}) \underset{\sim}{Z}_{\mathcal{L}} \underset{\sim}{Z}_C^{-1}] \underline{V}_0\end{aligned} \tag{2-60a}$$

$$\underline{I}(\mathcal{L}) = -j \sin(\beta\mathcal{L}) \underset{\sim}{Z}_C^{-1} \underline{V}_0 + [\cos(\beta\mathcal{L}) \underset{\sim}{1}_n + j \sin(\beta\mathcal{L}) \underset{\sim}{Z}_C^{-1} \underset{\sim}{Z}_0] \underline{I}(0) \tag{2-60b}$$

The terminal voltages can be obtained from the solution of (2-60) for the terminal currents, $\underline{I}(0)$ and $\underline{I}(\mathcal{L})$, with the equations for the terminal networks

$$\underline{V}(0) = \underline{V}_0 - \underset{\sim}{Z}_0 \underline{I}(0) \tag{2-61a}$$

$$\underline{V}(\ell) = \underline{V}_{\ell} + \underset{\sim}{Z}_{\ell}\,\underline{I}(\ell) \tag{2-61b}$$

2.5.2 Transmission Lines Consisting of Imperfect (Lossy) Conductors in a Lossless, Homogeneous Medium, XTALK2

This section considers the (n+1) conductor transmission lines considered in the previous section and shown in Figure 2-8. However, the transmission line conductors are considered to be lossy. Computer program XTALK2 considers these cases.

The per-unit-length inductance and capacitance matrices are computed as in the previous section and satisfy the relation in (2-50). The entries in $\underset{\sim}{L}$ are given in (2-53), (2-54) and (2-55). The per-unit-length admittance matrix is given by

$$\underset{\sim}{Y} = j\omega\underset{\sim}{C} = j\,\frac{\omega}{v^2}\,\underset{\sim}{L}^{-1} \tag{2-62}$$

The per-unit-length impedance matrix is given by

$$\underset{\sim}{Z} = \underset{\sim}{R}_c + j\omega\,\underset{\sim}{L}_c + j\omega\,\underset{\sim}{L} \tag{2-63}$$

where the entries in $\underset{\sim}{R}_c$ and $\underset{\sim}{L}_c$ are due to imperfect conductors. The entries in $\underset{\sim}{R}_c$ and $\underset{\sim}{L}_c$ are given in (2-5) and these matrices can be separated as [1]

$$\underset{\sim}{R}_c + j\omega\,\underset{\sim}{L}_c = (r_{c_0} + j\omega\ell_{c_0})\,\underset{\sim}{U}_n + \underset{\sim}{Z}_D \tag{2-64}$$

where $\underset{\sim}{U}_n$ is the nχn unit matrix with one's in every position, i.e., $[\underset{\sim}{U}_n]_{ij}=1$, and $\underset{\sim}{Z}_D$ is a diagonal matrix with

$$[\underset{\sim}{Z}_D]_{ii} = r_{c_i} + j\omega\ell_{c_i} \tag{2-65}$$

and $[\underset{\sim}{Z}_D]_{ij} = 0$ for i, j=1, ---, n and $i \neq j$. The calculation of the wire

self impedances, $r_{c_i} + j\omega \ell_{c_i}$, and the reference conductor self impedance, $r_{c_0} + j\omega \ell_{c_0}$, is discussed in section 2.4.

2.5.3 Transmission Lines Consisting of Perfect Conductors in a Lossless, Inhomogeneous Medium, FLATPAK

This section considers (n+1) conductor transmission lines consisting of (n+1) perfect conductors in a lossless, inhomogeneous medium. For example, dielectric insulations surrounding wires result in an inhomogeneous medium (dielectric insulation and the surrounding free space). The computer program FLATPAK considers a specific case of flatpack or ribbon cables. A ribbon cable consists of (n+1) identical wires with identical cylindrical dielectric insulations bonded together in a linear array as shown in Figure 2-9.

In this case, the relationship in (2-50) relating the per-unit-length inductance and capacitance matrices no longer holds. Clearly the surrounding medium does not influence the per-unit-length inductance matrix since the surrounding medium is considered to be homogeneous in its permeability characteristic, μ_v. Therefore, one may compute the per-unit-length capacitance matrix with the wire dielectric insulations removed, denoted by $\underset{\sim}{C}_0$, and determine $\underset{\sim}{L}$ through (2-50) as

$$\underset{\sim}{L} = \mu_v \, \varepsilon_v \, \underset{\sim}{C}_0^{-1} \tag{2-66}$$

Therefore, one needs to compute the per-unit-length capacitance matrix with <u>and</u> without the wire dielectric insulations present. A digital computer program, GETCAP, has been written to compute the per-unit-length capacitance matrices of ribbon cables. This program is described in detail in Volume II of this series [8].

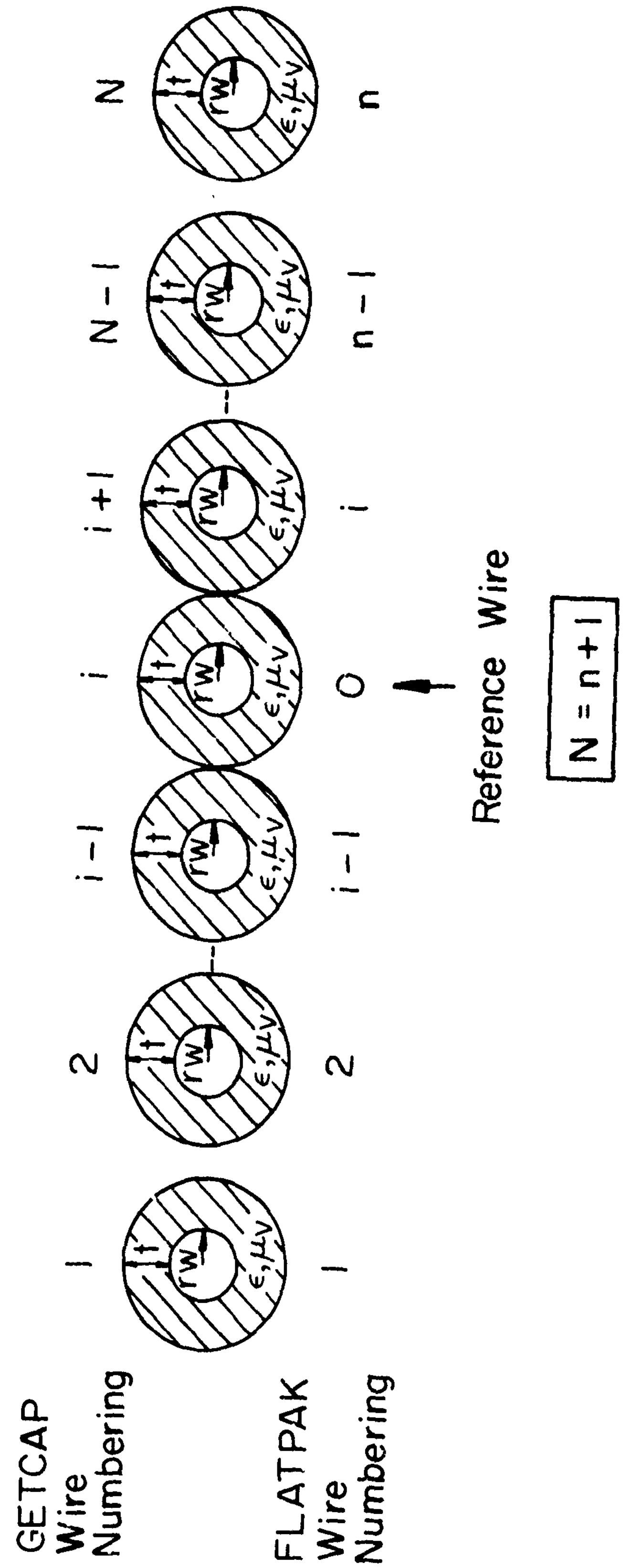


Fig. 2-9. An (n+1) wire ribbon (flatpack) cable.

The per-unit-length impedance and admittance matrices become

$$\underset{\sim}{Z} = j\omega \underset{\sim}{L} \tag{2-67a}$$

$$\underset{\sim}{Y} = j\omega \underset{\sim}{C} \tag{2-67b}$$

The transformation matrix, $\underset{\sim}{T}$, which diagonalizes the matrix product $\underset{\sim}{Y}\,\underset{\sim}{Z}$ must therefore diagonalize the product $\underset{\sim}{C}\,\underset{\sim}{L}$ as

$$\begin{aligned} \underset{\sim}{T}^{-1}\,\underset{\sim}{Y}\,\underset{\sim}{Z}\,\underset{\sim}{T} &= -\omega^2\,\underset{\sim}{T}^{-1}\,\underset{\sim}{C}\,\underset{\sim}{L}\,\underset{\sim}{T} \\ &= -\omega^2\,\underset{\sim}{\Lambda}^2 \end{aligned} \tag{2-68}$$

In addition, it can be shown that [1]

$$\underset{\sim}{T}^{-1} = \underset{\sim}{T}^{t}\,\underset{\sim}{C}^{-1} \tag{2-69}$$

where $\underset{\sim}{T}^{t}$ is the transpose of $\underset{\sim}{T}$. A digital computer subroutine NROOT (which uses subroutine EIGEN) is used to accomplish this reduction and is discussed in a later section.

2.5.4 Transmission Lines Consisting of Imperfect (Lossy) Conductors in a Lossless, Inhomogeneous Medium, FLATPAK2

This section considers (n+1) conductor transmission lines consisting of (n+1) lossy conductors in a lossless, inhomogeneous medium. The program FLATPAK2 considers a particular case of flatpack or ribbon cables discussed in the previous section.

The per-unit-length capacitance and inductance matrices are computed assuming perfect conductors and can be obtained with GETCAP as described in the previous section.

The self impedances of the wires are identical since the wires in the ribbon cable are typically identical. Therefore the pre-unit-length

impedance and admittance matrices become

$$\underset{\sim}{Z} = z(\underset{\sim}{U}_n + \underset{\sim}{1}_n) + j\omega\underset{\sim}{L} \tag{2-70a}$$

$$\underset{\sim}{Y} = j\omega\underset{\sim}{C} \tag{2-70b}$$

where $z = r + j\omega\ell$ is the self impedance of each wire.

III. PROGRAM CODE DESCRIPTIONS

In this chapter, the content of each program will be described by card. (Each program is labeled in columns 72-80 with the card number.) All programs were written in double precision arithmetic and the program listings are given in Appendix A - Appendix D. A table is provided with each listing which shows the changes which are required to convert each program to single precision arithmetic. Listings of two of the required subroutines, NROOT and EIGEN, are provided in Appendix E - Appendix F. The remaining required subroutines, LEQT1C and EIGCC, are a part of the IMSL (International Mathematical and Statistical Library) package [9]. Appropriate alternate subroutines can be substituted for LEQT1C and EIGCC if the IMSL package is not available on the user's system.

3.1 Program XTALK

A listing of XTALK is given in Appendix A.

Cards 001 through 047 contain general comments concerning the applicability of the program. This format will be followed in the other programs.

Cards 048 through 053 are comment cards pointing out that all arrays must be properly dimensioned for each problem before using the program.

Cards 054 through 059 dimension the arrays and declare variable types.

Card 060 gives the value of π and the speed of light in free space.

Cards 061 through 065 define the complex numbers 1+j0,0+j0,and 0+j1 as well as other constants.

Cards 071through 118 read and print an initial portion of the input data.

Cards 123 through 170 read and print the line dimensions and compute the entries in the characteristic impedance matrix. The entries in the characteristic impedance matrix, $\underset{\sim}{Z}_C$, are related to the per-unit-length inductance matrix for the three structure types given in (2-53), (2-54) and (2-55) by $\underset{\sim}{Z}_C = \nu \underset{\sim}{L}$. Cards 132 through 139 compute the main diagonal entries of $\underset{\sim}{Z}_C$. Cards 141 through 170 compute the off-diagonal entries. The n$\times$1 complex

arrays V1 and V2 are used to temporarily store the Z_i and Y_i coordinates or the r_i and Θ_i coordinates of the wires in the real parts of the arrays (see Figure 4-1, Figure 4-2, Figure 4-3). The nχn complex array M1 is used to temporarily store the characteristic impedance matrix in the real parts. Although the actual quantities stored are real, it was decided to use the real parts of these complex arrays to store these quantities rather than define additional real arrays. V1, V2 and M1 will be needed (as complex arrays) later.

Cards 175 through 181 compute the inverse of the characteristic impedance matrix which is temporarily stored in the real part of the nχn complex array M2. M2 will be needed (as a complex array) later. The matrix inverse is computed with subroutine LEQT1C which is described in section 3.5.

Cards 190 through 226 read and print the entries in the terminal impedance characterizations. These matrix characterizations are given in (2-30) for the Thevenin Equivalent characterization and in (2-34) for the Norton Equivalent characterization. The nχ1 complex arrays I0 and IL store the entries in $\underline{I}(0)$ and $\underline{I}(\mathcal{L})$, respectively, for the Norton Equivalent in (2-34) or $\underline{V}(0)$ and $\underline{V}(\mathcal{L})$, respectively, for the Thevenin Equivalent in (2-30). The nχn complex arrays Y0 and YL store the entries in $\underset{\sim}{Y}_0$ and $\underset{\sim}{Y}_{\mathcal{L}}$, respectively, for the Norton Equivalent in (2-34) or $\underset{\sim}{Z}_0$ and $\underset{\sim}{Z}_{\mathcal{L}}$, respectively, for the Thevenin Equivalent in (2-30).

Cards 231 through 291 contain certain matrix and vector multiplications which are independent of frequency. If one requests the analysis to be done at more than one frequency (such as in computing the frequency response of the line), then these time-consuming multiplications need be computed only for the first frequency and need not be recomputed for the additional fre-

quencies. To explain these cards, consider the similarity of the forms of the equations for the Norton Equivalent characterization given in (2-58) and the Thevenin Equivalent characterization given in (2-60). The analogous variables in these two equations are summarized as:

(2-58)	(2-60)
$\underset{\sim}{Y}_{\ell}$	$\underset{\sim}{Z}_{\ell}$
$\underset{\sim}{Y}_0$	$\underset{\sim}{Z}_0$
$\underset{\sim}{Z}_C$	$\underset{\sim}{Z}_C^{-1}$
$\underset{\sim}{Z}_C^{-1}$	$\underset{\sim}{Z}_C$
$\underline{I}_0$	$\underline{V}_0$
$\underline{I}_{\ell}$	$-\underline{V}_{\ell}$
$\underline{V}(0)$	$\underline{I}(0)$
$\underline{V}(\ell)$	$\underline{I}(\ell)$

Therefore equations (2-58) can be programmed and used for both cases if analogous variables are substituted. Cards 231 through 240 swap the entries in M1 and M2 if the Thevenin Equivalent characterization is chosen. Cards 251 through 291 form the quantities in (2-58)

	Array	
$\underset{\sim}{Z}_C \underset{\sim}{Y}_0$	M1	(3-1a)
$\underset{\sim}{Y}_{\ell} \underset{\sim}{Z}_C \underset{\sim}{Y}_0 + \underset{\sim}{Z}_C^{-1}$	M2	(3-1b)
$\underset{\sim}{Z}_C \underline{I}_0$	V1	(3-1c)
$\underset{\sim}{Y}_{\ell} \underset{\sim}{Z}_C \underline{I}_0$	V2	(3-1d)

for the Norton Equivalent characterization or the quantities in (2-60)

	Array	
$\underset{\sim}{Z}_C^{-1} \underset{\sim}{Z}_0$	M1	(3-2a)
$\underset{\sim}{Z}_{\ell} \underset{\sim}{Z}_C^{-1} \underset{\sim}{Z}_0 + \underset{\sim}{Z}_C$	M2	(3-2b)

$$\underset{\sim}{Z}_C^{-1} \underline{V}_0 \qquad\qquad V1 \qquad\qquad (3\text{-}2c)$$

$$\underset{\sim}{Z}_{\mathcal{L}} \underset{\sim}{Z}_C^{-1} \underline{V}_0 \qquad\qquad V2 \qquad\qquad (3\text{-}2d)$$

for the Thevenin Equivalent characterization.

Cards 295 through 300 read the frequency and form

$$\beta\mathcal{L} = \frac{2\pi f}{v}\mathcal{L} \tag{3-3a}$$

$$\sin(\beta\mathcal{L}) \tag{3-3b}$$

$$\cos(\beta\mathcal{L}) \tag{3-3c}$$

Cards 306 through 316 form equation (2-58a) for the Norton Equivalent characterization or (2-60a) for the Thevenin Equivalent characterization. These equations are solved with subroutine LEQT1C in card 320. The solutions ($\underline{V}(0)$ for (2-58a) or $\underline{I}(0)$ for (2-60a)) are stored in the array B.

Cards 332 through 336 form equation (2-58b) or (2-60b) and the entries in $\underline{V}(\mathcal{L})$ for (2-58b) or $\underline{I}(\mathcal{L})$ for (2-60b) are stored in the array WA.

Cards 337 through 365 print the terminal voltages $\underline{V}(0)$ and $\underline{V}(\mathcal{L})$. Cards 337 through 352 form the terminal voltages, if the Thevenin Equivalent characterization is chosen, from

$$\underline{V}(0) = \underline{V}_0 - \underset{\sim}{Z}_0 \underline{I}(0) \tag{3-4a}$$

$$\underline{V}(\mathcal{L}) = \underline{V}_{\mathcal{L}} + \underset{\sim}{Z}_{\mathcal{L}} \underline{I}(\mathcal{L}) \tag{3-4b}$$

since the elements of the arrays B and WA are the following:

Array	Norton	Thevenin
B	$\underline{V}(0)$	$\underline{I}(0)$
WA	$\underline{V}(\mathcal{L})$	$\underline{I}(\mathcal{L})$

Cards 353 through 365 print the resulting terminal voltages, $\underline{V}(0)$ and $\underline{V}(\mathcal{L})$.

3.2 Program XTALK2

A listing of XTALK2 is given in Appendix B.

Cards 001 through 190 have the same purpose and are of the same general structure as cards 001 through 181 in XTALK. The slight exceptions are that instead of computing the characteristic impedance matrix and its inverse as is done in XTALK, the per-unit-length capacitance matrix and its inverse are computed here. The per-unit-length inductance matrix, $\underset{\sim}{L}$, and capacitance matrix, $\underset{\sim}{C}$, are related by

$$\underset{\sim}{L}\,\underset{\sim}{C} = \frac{1}{\nu^2}\,\underset{\sim}{1}_n \tag{3-5a}$$

or

$$\nu\,\underset{\sim}{C} = \frac{1}{\nu}\,\underset{\sim}{L}^{-1} \tag{3-5b}$$

where ν is the velocity of light in the surrounding medium given by

$$\nu = \frac{1}{\sqrt{\varepsilon\mu}} = \frac{\nu_o}{\sqrt{\varepsilon_r \mu_r}} \tag{3-5c}$$

ε is the permittivity of the medium, μ is the permeability of the medium, ν_o is the velocity of light in free space ($\nu_o \cong 3 \times 10^8$ m/sec) and ε_r and μ_r are the relative permittivity and permeability, respectively. The characteristic impedance matrix is given by

$$\underset{\sim}{Z}_C = \nu\,\underset{\sim}{L} \tag{3-6}$$

Therefore $\underset{\sim}{C}^{-1} = \nu\,\underset{\sim}{Z}_C$. $\underset{\sim}{C}$ is stored in array C and $\underset{\sim}{C}^{-1}$ is stored in array CI.

Cards 195 through 223 read and print the characteristics of the reference conductor and the n wires to be using in calculating their self impedances.

Cards 233 through 269 read and print the termination network character-

istics and are identical to the corresponding cards in XTALK.

Cards 275 through 332 perform certain frequency independent matrix multiplications for reasons similar to those given in 3.1 for the analogous group of cards. These cards form, for the Norton or Thevenin Equivalent characterizations, certain quantities in Tables 2 and 3:

Array	Norton	Thevenin
M1	$\underset{\sim}{Y}_0 \underset{\sim}{C}^{-1}$	$\underset{\sim}{C} \underset{\sim}{Z}_0$
M2	$\underset{\sim}{Y}_{\mathcal{L}} \underset{\sim}{C}^{-1}$	$\underset{\sim}{C} \underset{\sim}{Z}_{\mathcal{L}}$
V1	$\underline{I}_0$	$\underset{\sim}{C} \underline{V}_0$
V2	$\underline{I}_{\mathcal{L}}$	$\underset{\sim}{C} \underline{V}_{\mathcal{L}}$

Cards 328 through 332 form the sums of entries in each row of $\underset{\sim}{C}$ and are stored in the array V3.

Cards 336 through 340 read the frequency and form the quantities $\omega=2\pi f$ and $j\omega$.

Cards 346 through 385 form the self impedances of the wires and the reference conductor. The equations for these self impedance terms are given in (2-42) through (2-49) in section 2.4. The self impedance of the reference conductor is stored as the complex variable Z0 and the self impedances of the n wires are temporarily stored in the array B.

Cards 391 through 398 compute the eigenvalues and eigenvectors of the product of the per-unit-length admittance and impedance matrices, $\underset{\sim}{Y}\underset{\sim}{Z}$. The per-unit-length admittance matrix is given by

$$\underset{\sim}{Y} = j\,\omega\,\underset{\sim}{C} \tag{3-7}$$

and the per-unit-length impedance matrix is given by

$$\underset{\sim}{Z} = z_0\,\underset{\sim}{U}_n + \underset{\sim}{Z}_D + j\,\omega\,\underset{\sim}{L} \tag{3-8}$$

where $\underset{\sim}{U}_n$ is an nχn unit matrix with ones in every position, z_0 is the self impedance of the reference conductor and $\underset{\sim}{Z}_D$ is an nχn diagonal matrix with the self impedance of the i-th wire in the i-th row and i-th column. The matrix product becomes (with the relation in (3-5a))

$$\underset{\sim}{Y}\,\underset{\sim}{Z} = j\omega\underset{\sim}{C}\,[z_0\,\underset{\sim}{U}_n + \underset{\sim}{Z}_D + j\omega\underset{\sim}{L}] = j\omega z_0\,\underset{\sim}{C}\,\underset{\sim}{U}_n + j\omega\underset{\sim}{C}\,\underset{\sim}{Z}_D - \frac{\omega^2}{\nu^2}\,\underset{\sim}{1}_n \qquad (3\text{-}9)$$

Note that $\underset{\sim}{C}\,\underset{\sim}{U}_n$ is simply on nχn matrix with the sum of all elements in the i-th row of $\underset{\sim}{C}$ in each of the entries in the i-th row of $\underset{\sim}{C}\,\underset{\sim}{U}_n$. These quantities were previously stored in the array V3. The subroutine EIGCC computes the nχl eigenvectors of $\underset{\sim}{Y}\underset{\sim}{Z}$, $\underline{T}_i$, and their associated eignenvectors, γ_i^2. The matrix T = $[\underline{T}_1, \underline{T}_2, ---, \underline{T}_n]$ will diagonalize $\underset{\sim}{Y}\underset{\sim}{Z}$ as [1]

$$\underset{\sim}{T}^{-1}\,\underset{\sim}{Y}\,\underset{\sim}{Z}\,\underset{\sim}{T} = \underset{\sim}{\gamma}^2 \qquad (3\text{-}10)$$

where $\underset{\sim}{\gamma}^2$ is an nχn diagonal matrix with γ_i^2 in the i-th position on the main diagonal. This is required in Tables 2 and 3. $\underset{\sim}{T}$ is stored in array T and the n entries on the main diagonal of $\underset{\sim}{\gamma}^2$ are temporarily stored in the array B.

Cards 403 through 410 compute the inverse of $\underset{\sim}{T}$ which is stored in array TI.

Cards 416 through 448 compute certain other quantities in Tables 2 and 3. These are

Array	Norton	Thevenin
YO	$\underset{\sim}{Y}_0^* = \underset{\sim}{T}^{-1}\,\underset{\sim}{Y}_0\,\underset{\sim}{C}^{-1}\,\underset{\sim}{T}$	$\underset{\sim}{Z}_0^* = \underset{\sim}{T}^{-1}\,\underset{\sim}{C}\,\underset{\sim}{Z}_0\,\underset{\sim}{T}$
YL	$\underset{\sim}{Y}_\ell^* = \underset{\sim}{T}^{-1}\,\underset{\sim}{Y}_\ell\,\underset{\sim}{C}^{-1}\,\underset{\sim}{T}$	$\underset{\sim}{Z}_\ell^* = \underset{\sim}{T}^{-1}\,\underset{\sim}{C}\,\underset{\sim}{Z}_\ell\,\underset{\sim}{T}$
IO	$\underline{I}_0^* = \underset{\sim}{T}^{-1}\,\underline{I}_0$	$\underline{V}_0^* = \underset{\sim}{T}^{-1}\,\underset{\sim}{C}\,\underline{V}_0$
IL	$\underline{I}_\ell^* = \underset{\sim}{T}^{-1}\,\underline{I}_\ell$	$-\underline{V}_\ell^* = -\underset{\sim}{T}^{-1}\,\underset{\sim}{C}\,\underline{V}_\ell$

Array	Norton	Thevenin
EP	$\underset{\sim}{E}^{+} = \frac{1}{2}(e^{\underset{\sim}{\gamma}\mathcal{L}} + e^{-\underset{\sim}{\gamma}\mathcal{L}})$	$\underset{\sim}{E}^{+} = \frac{1}{2}(e^{\underset{\sim}{\gamma}\mathcal{L}} + e^{-\underset{\sim}{\gamma}\mathcal{L}})$
EN	$\underset{\sim}{E}^{-} = \frac{1}{2}(e^{\underset{\sim}{\gamma}\mathcal{L}} - e^{-\underset{\sim}{\gamma}\mathcal{L}})$	$\underset{\sim}{E}^{-} = \frac{1}{2}(e^{\underset{\sim}{\gamma}\mathcal{L}} - e^{-\underset{\sim}{\gamma}\mathcal{L}})$
G	$\underset{\sim}{\Lambda} = \frac{1}{j\omega}\underset{\sim}{\gamma}$	$\underset{\sim}{\Lambda} = \frac{1}{j\omega}\underset{\sim}{\gamma}$

Cards 449 through 458 form equation (1) in Tables 2 and 3. This equation is solved with subroutine LEQT1C in card 462 with the result stored in array B as:

Array	Norton	Thevenin
B	$\underline{V}^{*}(0)$	$\underline{I}^{*}(0)$

Cards 480 through 484 form equation (2) in Tables 2 and 3 with the result stored as

Array	Norton	Thevenin
G	$\underline{V}^{*}(\mathcal{L})$	$\underline{I}^{*}(\mathcal{L})$

Cards 485 through 531 form the terminal voltages $\underline{V}(0)$ and $\underline{V}(\mathcal{L})$ by back transforming according to equation (9) in Tables 2 and 3.

3.3 Program FLATPAK

A listing of FLATPAK is given in Appendix C.

Cards 001 through 057 are similar to corresponding cards in the previous programs.

Cards 062 through 097 read a portion of the input data describing the structure of the line. The per-unit-length capacitance matrix, $\underset{\sim}{C}$, (computed with GETCAP) is stored in array C. The per-unit-length capacitance matrix with the wire insulations removed, $\underset{\sim}{C}_0$, (computed with GETCAP) is stored in array C0.

Cards 105 through 113 compute the eigenvectors and corresponding eigen-

values of the matrix product $\underset{\sim}{C}\,\underset{\sim}{L}$. Subroutine NROOT computes the matrix $\underset{\sim}{K}$ such that

$$\underset{\sim}{K}^{-1}\,\underset{\sim}{C}^{-1}\,\underset{\sim}{C}_0\,\underset{\sim}{K} = \underset{\sim}{\psi} \tag{3-11}$$

such that $\underset{\sim}{\psi}$ is a diagonal matrix. $\underset{\sim}{K}$ is stored in array TI. The problem of interest is finding $\underset{\sim}{T}$ such that

$$\underset{\sim}{T}^{-1}\,\underset{\sim}{C}\,\underset{\sim}{L}\,\underset{\sim}{T} = \underset{\sim}{\gamma}^2 \tag{3-12}$$

where

$$\underset{\sim}{L} = \frac{1}{\nu_o^2}\,\underset{\sim}{C}_0 \tag{3-13}$$

Taking the inverse of both sides of (3-11) results in

$$\underset{\sim}{K}^{-1}\,\underset{\sim}{C}_0^{-1}\,\underset{\sim}{C}\,\underset{\sim}{K} = \underset{\sim}{\psi}^{-1} \tag{3-14}$$

Taking the transpose of both sides of (3-14) results in

$$\underset{\sim}{K}^t\,\underset{\sim}{C}\,\underset{\sim}{C}_0^{-1}\,\underset{\sim}{K}^{-1^t} = \underset{\sim}{\psi}^{-1} \tag{3-15}$$

(Since $\underset{\sim}{C}$ and $\underset{\sim}{C}_0$ are symmetric, $\underset{\sim}{C}^t = \underset{\sim}{C}$ and $\underset{\sim}{C}_0^{-1^t} = \underset{\sim}{C}_0^{-1}$. Also ψ is diagonal. Therefore $\underset{\sim}{\psi}^{-1^t} = \underset{\sim}{\psi}^{-1}$.) Thus comparing (3-15) to (3-12) and using (3-13) we identify

$$\underset{\sim}{K} = \underset{\sim}{T}^{-1^t} \tag{3-16a}$$

$$\frac{1}{\nu_o^2}\,\underset{\sim}{\psi}^{-1} = \underset{\sim}{\gamma}^2 \tag{3-16b}$$

and $\underset{\sim}{T}^{-1^t}$ is stored in array C and array G contains the square roots of entries on the main diagonal of $\underset{\sim}{\gamma}^2$, $\underset{\sim}{\gamma}$.

Cards 114 through 128 compute $\underset{\sim}{T}$ and $\underset{\sim}{\gamma}^{-1}$ if the Thevenin Equivalent characterization is chosen. Thus, contained in arrays TI and G are:

Array	Norton	Thevenin
TI	$\underset{\sim}{T}^{-1^t}$	$\underset{\sim}{T}$
G	$\underset{\sim}{\gamma}$	$\underset{\sim}{\gamma}^{-1}$

Cards 138 through 175 read and print the termination network characteristics and are identical to the corresponding cards in the previous programs.

Cards 182 through 220 form the following frequency independent quantities (see Tables 2 and 3)

Array	Norton	Thevenin
YO	$\underset{\sim}{Y}_0^* = \underset{\sim}{T}^{-1} \underset{\sim}{Y}_0 \underset{\sim}{C}^{-1} \underset{\sim}{T}$	$\underset{\sim}{Z}_0^* = \underset{\sim}{T}^{-1} \underset{\sim}{C} \underset{\sim}{Z}_0 \underset{\sim}{T}$
YL	$\underset{\sim}{Y}_\ell^* = \underset{\sim}{T}^{-1} \underset{\sim}{Y}_\ell \underset{\sim}{C}^{-1} \underset{\sim}{T}$	$\underset{\sim}{Z}_\ell^* = \underset{\sim}{T}^{-1} \underset{\sim}{C} \underset{\sim}{Z}_\ell \underset{\sim}{T}$
IO	$\underline{I}_0^* = \underset{\sim}{T}^{-1} \underline{I}_0$	$\underline{V}_0^* = \underset{\sim}{T}^{-1} \underset{\sim}{C} \underline{V}_0$
IL	$\underline{I}_\ell^* = \underset{\sim}{T}^{-1} \underline{I}_\ell$	$-\underline{V}_\ell^* = -\underset{\sim}{T}^{-1} \underset{\sim}{C} \underline{V}_\ell$

Since $\underset{\sim}{T}^{-1}$ satifies

$$\underset{\sim}{T}^{-1} = \underset{\sim}{T}^t \underset{\sim}{C}^{-1} \tag{3-17}$$

then

$$\underset{\sim}{T}^{-1^t} = \underset{\sim}{C}^{-1} \underset{\sim}{T} \tag{3-18}$$

and these relations allow the entries in the arrays YO, YL, IO and IL to be more easily generated as:

Array	Norton	Thevenin
YO	$\underset{\sim}{Y}_0^* = \underset{\sim}{T}^{-1} \underset{\sim}{Y}_0 \underset{\sim}{T}^{-1^t}$	$\underset{\sim}{Z}_0^* = \underset{\sim}{T}^t \underset{\sim}{Z}_0 \underset{\sim}{T}$
YL	$\underset{\sim}{Y}_\ell^* = \underset{\sim}{T}^{-1} \underset{\sim}{Y}_\ell \underset{\sim}{T}^{-1}$	$\underset{\sim}{Z}_\ell^* = \underset{\sim}{T}^t \underset{\sim}{Z}_\ell \underset{\sim}{T}$
IO	$\underline{I}_0^* = \underset{\sim}{T}^{-1} \underline{I}_0$	$\underline{V}_0^* = \underset{\sim}{T}^t \underline{V}_0$
IL	$\underline{I}_\ell^* = \underset{\sim}{T}^{-1} \underline{I}_\ell$	$-\underline{V}_\ell^* = -\underset{\sim}{T}^t \underline{V}_\ell$

Cards 224 through 227 read the frequency and compute $\omega = 2\pi f$.

Cards 233 through 248 form equation (1) in Tables 2 and 3.

Equation (1) in Tables 2 and 3 is solved with subroutine LEQT1C in card 252.

Cards 264 through 268 form equation (2) in Tables 2 and 3. The arrays B and WA now contain, with respect to Tables 2 and 3:

Array	Norton	Thevenin
B	$\underline{V}^*(0)$	$\underline{I}^*(0)$
WA	$\underline{V}^*(\mathcal{L})$	$\underline{I}^*(\mathcal{L})$

The terminal voltages, $\underline{V}(0)$ and $\underline{V}(\mathcal{L})$ are computed in cards 269 through 286 by back transforming $\underline{V}^*(0)$ and $\underline{V}^*(\mathcal{L})$ through (see Tables 2 and 3)

Norton

$$\underline{V}(0) = \underset{\sim}{C}^{-1}\,\underset{\sim}{T}\,\underline{V}^*(0) = \underset{\sim}{T}^{-1^t}\,\underline{V}^*(0)$$

$$\underline{V}(\mathcal{L}) = \underset{\sim}{C}^{-1}\,\underset{\sim}{T}\,\underline{V}^*(\mathcal{L}) = \underset{\sim}{T}^{-1^t}\,\underline{V}^*(\mathcal{L})$$

Thevenin

$$\underline{V}^*(0) = \underline{V}_0^* - \underset{\sim}{Z}_0^*\,\underline{I}^*(0)$$

$$\underline{V}(0) = \underset{\sim}{C}^{-1}\,\underset{\sim}{T}\,\underline{V}^*(0) = \underset{\sim}{T}^{-1^t}\,\underline{V}^*(0)$$

$$\underline{V}^*(\mathcal{L}) = \underline{V}_{\mathcal{L}}^* + \underset{\sim}{Z}_{\mathcal{L}}^*\,\underline{I}^*(\mathcal{L})$$

$$\underline{V}(\mathcal{L}) = \underset{\sim}{C}^{-1}\,\underset{\sim}{T}\,\underline{V}^*(\mathcal{L}) = \underset{\sim}{T}^{-1^t}\,\underline{V}^*(\mathcal{L})$$

Cards 287 through 301 print the resulting terminal voltages.

3.4 Program FLATPAK2

A listing of FLATPAK2 is given in Appendix D.

Cards 001 through 106 are similar to corresponding cards (001 through 097) in FLATPAK.

Cards 112 through 133 compute the inverse of the per-unit-length

capacitance matrix which is stored in array CI. The per-unit-length inductance matrix, $\underset{\sim}{L}$, is also computed from the relation

$$\underset{\sim}{L} = \frac{1}{\nu^2} \underset{\sim}{C}_0^{-1} \tag{3-19}$$

Cards 138 through 144 read the characteristics of the wires in the ribbon cable (all wires are assumed to be identical) for use in computing their self impedances.

Cards 154 through 191 read and print the characteristics of the termination networks and are identical to the corresponding cards in the previous programs.

Cards 197 through 262 form certain frequency independent quantities in Tables 2 and 3:

Array	Norton	Thevenin
M1	$\underset{\sim}{Y}_0 \underset{\sim}{C}^{-1}$	$\underset{\sim}{C} \underset{\sim}{Z}_0$
M2	$\underset{\sim}{Y}_\ell \underset{\sim}{C}^{-1}$	$\underset{\sim}{C} \underset{\sim}{Z}_\ell$
V1	$\underset{-}{I}_0$	$\underset{\sim}{C} \underset{-}{V}_0$
V2	$\underset{-}{I}_\ell$	$\underset{\sim}{C} \underset{-}{V}_\ell$

Cards 251 through 262 form the quantities $\underset{\sim}{C}\,\underset{\sim}{L}$ which is stored in array C0 and the sums of the elements in the i-th row of $\underset{\sim}{C}$ which are stored in array V3.

Cards 266 through 270 read the frequency and form $\omega = 2\pi f$ and $j\omega$.

Cards 274 through 283 form the self impedances of the wires which are stored in the complex variable Z (all wires are identical).

Cards 289 through 295 compute the transformation matrix $\underset{\sim}{T}$ such that

$$\underset{\sim}{T}^{-1} \underset{\sim}{Y} \underset{\sim}{Z} \underset{\sim}{T} = \underset{\sim}{\gamma}^2 \tag{3-20}$$

where $\underset{\sim}{\gamma}^2$ is a diagonal matrix and

$$\begin{aligned} \underset{\sim}{Y}\,\underset{\sim}{Z} &= j\omega \underset{\sim}{C}(z\,\underset{\sim}{U}_n + z\,\underset{\sim}{1}_n + j\omega \underset{\sim}{L}) \\ &= j\omega z\,\underset{\sim}{C}\,\underset{\sim}{U}_n + j\omega z\,\underset{\sim}{C} - \omega^2\,\underset{\sim}{C}\,\underset{\sim}{L} \end{aligned} \tag{3-21}$$

Subroutine EIGCC computes $\underset{\sim}{T}$ and stores it in array T and stores the entries on the main diagonal of $\underset{\sim}{\gamma}^2$ temporarily in Array B.

The inverse of $\underset{\sim}{T}$ is computed with LEQT1C in cards 300 through 307 and is stored in array TI.

Cards 313 through 345 compute certain quantities in Tables 2 and 3:

Array	Norton	Thevenin
Y0	$\underset{\sim}{Y}_0^* = \underset{\sim}{T}^{-1}\,\underset{\sim}{Y}_0\,\underset{\sim}{C}^{-1}\,\underset{\sim}{T}$	$\underset{\sim}{Z}_0^* = \underset{\sim}{T}^{-1}\,\underset{\sim}{C}\,\underset{\sim}{Z}_0\,\underset{\sim}{T}$
YL	$\underset{\sim}{Y}_\ell^* = \underset{\sim}{T}^{-1}\,\underset{\sim}{Y}_\ell\,\underset{\sim}{C}^{-1}\,\underset{\sim}{T}$	$\underset{\sim}{Z}_\ell^* = \underset{\sim}{T}^{-1}\,\underset{\sim}{C}\,\underset{\sim}{Z}_\ell\,\underset{\sim}{T}$
I0	$\underline{I}_0^* = \underset{\sim}{T}^{-1}\,\underline{I}_0$	$\underline{V}_0^* = \underset{\sim}{T}^{-1}\,\underset{\sim}{C}\,\underline{V}_0$
IL	$\underline{I}_\ell^* = \underset{\sim}{T}^{-1}\,\underline{I}_\ell$	$-\underline{V}_\ell^* = -\underset{\sim}{T}^{-1}\,C\,\underline{V}_\ell$
EP	$\underset{\sim}{E}^+ = \frac{1}{2}(e^{\underset{\sim}{\gamma}\ell} + e^{-\underset{\sim}{\gamma}\ell})$	$\underset{\sim}{E}^+ = \frac{1}{2}(e^{\underset{\sim}{\gamma}\ell} + e^{-\underset{\sim}{\gamma}\ell})$
EN	$\underset{\sim}{E}^- = \frac{1}{2}(e^{\underset{\sim}{\gamma}\ell} - e^{-\underset{\sim}{\gamma}\ell})$	$\underset{\sim}{E}^- = \frac{1}{2}(e^{\underset{\sim}{\gamma}\ell} - e^{-\underset{\sim}{\gamma}\ell})$
G	$\underset{\sim}{\Lambda} = \frac{1}{j\omega}\,\underset{\sim}{\gamma}$	$\underset{\sim}{\Lambda} = \frac{1}{j\omega}\,\underset{\sim}{\gamma}$

Cards 346 through 355 form equation (1) in Tables 2 and 3 which is solved with subroutine LEQT1C in card 359.

Cards 376 through 380 form equation (2) in Tables 2 and 3. Thus the arrays B and G contain:

Arrays	Norton	Thevenin
B	$\underline{V}^*(0)$	$\underline{I}^*(0)$
G	$\underline{V}^*(\ell)$	$\underline{I}^*(\ell)$

Cards 381 through 406 form $\underline{V}(0)$ and $\underline{V}(\ell)$ by back transforming $\underline{V}^*(0)$ and $\underline{V}^*(\ell)$ as described in FLATPAK using the relations in Table 2 and Table 3:

$$\underline{V}(0) = \underset{\sim}{C}^{-1}\,\underset{\sim}{T}\,\underline{V}^*(0)$$
$$\underline{V}(\ell) = \underset{\sim}{C}^{-1}\,\underset{\sim}{T}\,\underline{V}^*(\ell)$$

Cards 407 through 427 print the terminal voltages.

3.5 Required Subroutines

The four programs require certain subroutines: LEQT1C, EIGCC, NROOT, and EIGEN. The individual programs require:

Program	Required Subroutines
XTALK	LEQT1C
XTALK2	LEQT1C, EIGCC
FLATPAK	LEQT1C, NROOT, EIGEN
FLATPAK2	LEQT1C, EIGCC

The required subroutines must follow the main program and precede the data cards.

3.5.1 Subroutine LEQT1C

Subroutine LEQT1C is a general subroutine for solving a system of n simultaneous, complex equations. The program is a part of the IMSL (International Mathematical and Statistical Library) package [9].

The subroutine solves the system of equations

$$\underset{\sim}{A}\,\underset{\sim}{X} = \underset{\sim}{B} \qquad (3\text{-}22)$$

where $\underset{\sim}{A}$ is an nχn complex matrix, $\underset{\sim}{B}$ is an nχm complex matrix and $\underset{\sim}{X}$ is an nχm complex matrix whose columns, $\underline{X}_i$, are solutions to

$$\underset{\sim}{A}\,\underline{X}_i = \underline{B}_i \tag{3-23}$$

where $\underline{B}_i$ is the i-th column of $\underset{\sim}{B}$.

The calling statement is

```
CALL LEQT1C(A,N,N,B,N,M,WA,IER)
```

where

$$A \rightarrow \underset{\sim}{A}$$

$$B \rightarrow \underset{\sim}{B}$$

$$N \rightarrow n$$

$$M \rightarrow m$$

and WA is a complex working vector of length n. IER is an error parameter which is returned as[1]

IER = 128 → no solution error

IER = 129 → $\underset{\sim}{A}$ is algorithmically singular [9].

The solution $\underset{\sim}{X}$ is returned in array B and the contents of array A are destroyed.

Subroutine LEQT1C can be used to find the inverse of an nχn matrix by computing

$$\underset{\sim}{A}\,\underset{\sim}{X} = \underset{\sim}{1}_n \tag{3-24}$$

where $\underset{\sim}{1}_n$ is the nχn identity matrix. Thus the solution is $\underset{\sim}{X} = \underset{\sim}{A}^{-1}$. LEQT1C

[1]The solution error parameter is printed out whenever LEQT1C is used. The printed error is IER-128 so that the solution error should be 0.

is used in numerous places to invert real matrices by defining the real part of $\tilde{A}$ to be the matrix and the imaginary part to be zero. Upon solution, the real part of $\tilde{X}$ is the inverse of the real matrix, $\tilde{A}$.

3.5.2 Subroutine EIGCC

Subroutine EIGCC is also a part of the IMSL subroutine package [9] and is used to find the eigenvalues and eigenvectors of an $n \chi n$ complex matrix, $\tilde{M}$. Denote the $n \chi 1$ (complex) eigenvectors, $\underline{T}_i$, of $\tilde{M}$ as $\underline{T}_1$, $\underline{T}_2$, ---, $\underline{T}_n$ and the corresponding (complex) eigenvalues as b_1, b_2, ---, b_n. EIGCC computes the $n \chi n$ matrix $\tilde{T} = [\underline{T}_1, \underline{T}_2, \underline{T}_3, ---, \underline{T}_n]$ such that

$$\tilde{T}^{-1} \tilde{M} \tilde{T} = \tilde{B} \tag{3-25}$$

where $\tilde{B}$ is an $n \chi n$ diagonal matrix with $[\tilde{B}]_{ii} = b_i$ and $[\tilde{B}]_{ij} = 0$ for i, j=1, ---, n and $i \neq j$.

The calling statement is

```
CALL EIGCC(M,N,N,2,B,T,WK,IER)
```

where WK is a real working vector of length 2n(n+1). IER is an error parameter which is returned as IER = 128 + J.[1] This indicates that the routine failed to converge on the j-th eigenvalue [9]. The precision of the eigenvector, eigenvalue solution is returned in the first position of array WK, WK(1), and indicates [9]

Solution Precision

WK (1) < 1 → Excellent

1 < WK (1) < 100 → Good

WK (1) > 100 → Poor

---

[1]The solution error is printed out as IER-128. A successful solution would then be indicated by 0.

The matrix $\underset{\sim}{T}$ is stored in the nχn array T and the eigenvalues, b_i, are stored in the nχ1 array B in the same order as the columns of T.

3.5.3 Subroutines NROOT and EIGEN

Subroutines NROOT and EIGEN are a set of subroutines from the IBM Scientific Subroutine Package (SSP) [10] which compute the eignevectors and eigenvalues ot the matrix product

$$\underset{\sim}{B}^{-1}\underset{\sim}{A} \qquad (3\text{-}26)$$

where $\underset{\sim}{A}$ and $\underset{\sim}{B}$ are nχn real, symmetric matrices and $\underset{\sim}{B}$ is positive definite. A listing of NROOT is provided in Appendix E and a listing of EIGEN is provided in Appendix F. These subroutines are used to find the eigenvalues and eigenvectors of the product of the per-unit-length capacitance, $\underset{\sim}{C}$, and inductance, $\underset{\sim}{L}$, matrices as

$$\underset{\sim}{C}\,\underset{\sim}{L} \qquad (3\text{-}27)$$

Subroutine NROOT calls subroutine EIGEN.

NROOT computes the nχn real matrix $\underset{\sim}{T}$ such that

$$\underset{\sim}{T}^{-1}\,\underset{\sim}{B}^{-1}\,\underset{\sim}{A}\,\underset{\sim}{T} = \underset{\sim}{G} \qquad (3\text{-}28)$$

where $\underset{\sim}{G}$ is an nχn diagonal matrix with $[\underset{\sim}{G}]_{ii} = g_i$ and $[\underset{\sim}{G}]_{ij} = 0$ for i, j=1, ---, n and i$\neq$j. The eigenvectors $\underline{T}_i$ correspond to the eigenvalues g_i and $\underset{\sim}{T} = [\underline{T}_1, \underline{T}_2, ---, \underline{T}_n]$.

The calling statement is

CALL NROOT(N,A,B,G,T,N*N)

where

Array

$$A \rightarrow \underset{\sim}{A}$$

$$B \rightarrow \underset{\sim}{B}$$

$$N \rightarrow n$$

$$G \rightarrow \underset{\sim}{G}$$

$$T \rightarrow \underset{\sim}{T}$$

The $n\chi 1$ array G returns the eigenvalues g_i in the same sequence as the columns (corresponding eigenvectors) of $\underset{\sim}{T}$.

The subroutine operates in the following manner [1,11]. NROOT first computes the $n\chi n$, real, orthogonal transformation matrix $\underset{\sim}{S}$ such that $(\underset{\sim}{S}^{-1} = \underset{\sim}{S}^t)$

$$\underset{\sim}{S}^t \underset{\sim}{B} \underset{\sim}{S} = \underset{\sim}{H} \tag{3-29}$$

where $\underset{\sim}{H}$ is an $n\chi n$ diagonal matrix with $[\underset{\sim}{H}]_{ii} = h_i$ and $[\underset{\sim}{H}]_{ij} = 0$ for i, j=1, ---, n. EIGEN is called for this calculation. Since $\underset{\sim}{B}$ is real, symmetric, positive definite, the eigenvalues of $\underset{\sim}{B}$, h_i, are real, nonzero and positive. Therefore NROOT forms the square root of $\underset{\sim}{H}$, $\underset{\sim}{H}^{1/2}$ and its inverse $\underset{\sim}{H}^{-1/2}$. NROOT then forms the products

$$\underset{\sim}{M} = \underset{\sim}{S} \underset{\sim}{H}^{-1/2} \tag{3-30}$$

and

$$\underset{\sim}{M}^t \underset{\sim}{A} \underset{\sim}{M} \tag{3-31}$$

which is real, symmetric. NROOT calls EIGEN once again to find the $n\chi n$ real, orthogonal matrix $\underset{\sim}{W}$ such that $(\underset{\sim}{W}^{-1} = \underset{\sim}{W}^t)$

$$\underset{\sim}{W}^t [\underset{\sim}{M}^t \underset{\sim}{A} \underset{\sim}{M}] \underset{\sim}{W} = \underset{\sim}{G} \tag{3-32}$$

and G is diagonal. The transformation matrix T is given by

$$T = S\, H^{-1/2}\, W \tag{3-33}$$

To show that T in fact diagonalizes $B^{-1} A$, form

$$\begin{aligned}
&T^{-1} B^{-1} A\, T = \\
&W^t H^{1/2} S^t B^{-1} A\, S\, H^{-1/2} W = \\
&W^t \underbrace{H^{1/2} \underbrace{S^t B^{-1} S}_{H^{-1}} H^{1/2}}_{1} \overset{1_n}{} \underbrace{H^{-1/2} S^t A\, S\, H^{-1/2}}_{M^t A M} W = G
\end{aligned} \tag{3-34}$$

The NROOT subroutine used in the program FLATPAK and shown in Appendix G is slightly different from the NROOT subroutine given in SSP [10]. The difference is that the eigenvectors in NROOT in Appendix G are not normalized. This is required for NROOT to be used in FLATPAK so that the transformation matrix T which diagonalizes the matrix product C L as

$$T^{-1} C\, L\, T = \gamma^2 \tag{3-35}$$

will satisfy the identity

$$T^{-1} = T^t C^{-1} \tag{3-36}$$

If the columns of T (the eigenvectors) are normalized, (3-36) will no longer be true.

IV. USER'S MANUAL

This section will serve as a user's manual for the use of the programs. All input data are punched on cards which must follow the main program (and any subroutines). The format of the data input cards as well as suggestions for program useage are included. All of the programs require three groups of data input:

Group I	Transmission Line Structure Characteristics Cards
Group II	Termination Network Characterization Cards Group II(a) Group II(b)
Group III	Frequency Cards

These card groups must follow the main program (and any required subroutines) in the above order. The data entries are either in Integer (I) format, e.g., 35, or in Exponential (E) format, e.g., 12.6E-3. All data entries must be right-justified in the assigned card column block.

In all four programs, the user must appropriately dimension all arrays for each problem. Comment cards are provided at the beginning of each program to assist the user in providing proper dimensions. All arrays must be properly dimensioned by repunching the dimension statement cards in a program before using the program.

4.1 The Frequency Cards, Group III

Each frequency card contains one and only one frequency for which an analysis is desired. The format of the frequency card is shown in Table 4. The frequency in Hertz is punched in columns 1-10 of each card and must be

TABLE 4

Format of the Frequency Group Cards, Group III

	card column	format
frequency (Hertz)	1-10	E

Total number = unlimited

right justified in the card block consisting of card columns 1-10. For example, if one wished to input a frequency of 1 M Hz, one may punch

```
                1 . E 6
                ↑ ↑ ↑ ↑
card columns    7 8 9 10
```

If, instead, the frequency was punched as

```
                1 . E 6
                ↑ ↑ ↑ ↑
card columns    6 7 8 9
```

The program would take this to be a frequency of 10^{60} Hertz (zeros are added to fill out the assigned card block). This right-justification of data in an assigned card block applies to all other data entries.

More than one frequency card may be included in the frequency card group. Each program will process the data provided by Groups I and II and compute the response at the frequency on the first frequency card. It will then recompute the response at each frequency on the remaining frequency cards. The program assumes that the data on card Groups I and II are to be used for all the remaining frequencies. If this is not intended by the user, then one may only run the program for one frequency at a time. This feature, however, can be quite useful. If the termination networks are purely resistive, i.e., frequency independent, then one may use as many frequency cards as desired in this frequency card group and the program will compute the response of the line at each frequency without the necessity for the user to input the data in Groups I and II for each additional frequency. Many of the time-consuming calculations which are independent of frequency need to be computed

only once so that this mode of useage will save considerable computation time when the response at many frequencies is desired. If, however, the termination network characteristics (in Group II) are complex (which implies frequency dependent), one must run the program for only one frequency at a time.

4.2 The Termination Network Characterization Cards, Group II

This group of cards conveys the terminal characteristics of the termination networks at the ends of the line, $x = 0$ and $x = \mathcal{L}$. The termination networks are characterized by either the Thevenin Equivalent or the Norton Equivalent characterization. These characterizations are of the form

$$\left.\begin{aligned} \underline{V}(0) &= \underline{V}_0 - \underset{\sim}{Z}_0\,\underline{I}(0) \\ \underline{V}(\mathcal{L}) &= \underline{V}_{\mathcal{L}} + \underset{\sim}{Z}_{\mathcal{L}}\,\underline{I}(\mathcal{L}) \end{aligned}\right\}\ \begin{array}{l}\text{Thevenin}\\ \text{Equivalent}\end{array} \qquad (4\text{-}1a)$$

$$\left.\begin{aligned} \underline{I}(0) &= \underline{I}_0 - \underset{\sim}{Y}_0\,\underline{V}(0) \\ \underline{I}(\mathcal{L}) &= -\underline{I}_{\mathcal{L}} + \underset{\sim}{Y}_{\mathcal{L}}\,\underline{V}(\mathcal{L}) \end{aligned}\right\}\ \begin{array}{l}\text{Norton}\\ \text{Equivalent}\end{array} \qquad (4\text{-}1b)$$

and are discussed in detail in section 2.3. The transmission line consists of n wires which are numbered from 1 to n and a reference conductor for the line voltages. The reference conductor is numbered as the zero (0) conductor. Thus $\underline{V}_0$, $\underline{V}_{\mathcal{L}}$, $\underline{I}_0$, $\underline{I}_{\mathcal{L}}$ are $n\chi 1$ vectors and $\underset{\sim}{Z}_0$, $\underset{\sim}{Z}_{\mathcal{L}}$, $\underset{\sim}{Y}_0$, $\underset{\sim}{Y}_{\mathcal{L}}$ are $n\chi n$ matrices which are assumed to be symmetric.

The impedance or admittance matrices $\underset{\sim}{Z}_0$ and $\underset{\sim}{Z}_{\mathcal{L}}$ or $\underset{\sim}{Y}_0$ and $\underset{\sim}{Y}_{\mathcal{L}}$, respectively, may either be "full" in which all entries are not necessarily zero or may be diagonal in which only the entries on the main diagonals are not necessarily zero and the off-diagonal entries are zero. The user may select one of four options for communicating the entries in the vectors and matrices in

(4-1). These are:

OPTION = 11 $\left\{\begin{array}{l}\text{Thevenin Equivalent representation;}\\ \text{diagonal impedance matrices, } \underset{\sim}{Z}_0 \text{ and } \underset{\sim}{Z}_\ell.\end{array}\right\}$

OPTION = 12 $\left\{\begin{array}{l}\text{Thevenin Equivalent representation;}\\ \text{full impedance matrices, } \underset{\sim}{Z}_0 \text{ and } \underset{\sim}{Z}_\ell.\end{array}\right\}$

OPTION = 21 $\left\{\begin{array}{l}\text{Norton Equivalent representation;}\\ \text{diagonal admittance matrices, } \underset{\sim}{Y}_0 \text{ and } \underset{\sim}{Y}_\ell.\end{array}\right\}$

OPTION = 22 $\left\{\begin{array}{l}\text{Norton Equivalent representation;}\\ \text{full admittance matrices, } \underset{\sim}{Y}_0 \text{ and } \underset{\sim}{Y}_\ell.\end{array}\right\}$

The structure and ordering of the data in Group II are given in Table 5 and can be summarized in the following manner. The first group of cards in Group II, Group II(a), will describe the entries on the main diagonal in $\underset{\sim}{Y}_0(\underset{\sim}{Z}_0)$, $Y_{0ii}(Z_{0ii})$, and $\underset{\sim}{Y}_\ell(\underset{\sim}{Z}_\ell)$, $Y_{\ell ii}(Z_{\ell ii})$, and the entries in $\underline{I}_0(\underline{V}_0)$, $I_{0i}(V_{0i})$, and $\underline{I}_\ell(\underline{V}_\ell)$, $I_{\ell i}(V_{\ell i})$. These cards must be in the order from i = 1 to i = n. Each of these entries is in general, complex. Therefore two card blocks are assigned for each entry; one for the real part and one for the imaginary part. For example, consider a 4 conductor line (3 wires and a reference conductor). Here n would be 3. Suppose the Thevenin Equivalent characterization is selected, with the following entries in the characterization matrices:

$$\underline{V}_0 = \begin{bmatrix} 1 + j2 \\ 3 + j5 \\ 6 + j4 \end{bmatrix} \qquad \underset{\sim}{Z}_0 = \begin{bmatrix} 7+j8 & 0 & 0 \\ 0 & j9 & 0 \\ 0 & 0 & 10+j11 \end{bmatrix}$$

$$\underline{V}_\ell = \begin{bmatrix} 12 \\ j13 \\ 14+j15 \end{bmatrix} \qquad \underset{\sim}{Z}_\ell = \begin{bmatrix} 16 & 0 & 0 \\ 0 & 17+j18 & 0 \\ 0 & 0 & j19 \end{bmatrix}$$

TABLE 5 (cont.)

Format of the Termination Network Characterization Cards, Group II

Group II(a)(total = n)

		card column	format
$Y_{0ii}(Z_{0ii})$	real part	1-10	E
	imaginary part	11-20	E
$I_{0i}(V_{0i})$	real part	21-30	E
	imaginary part	31-40	E
$Y_{\ell ii}(Z_{\ell ii})$	real part	41-50	E
	imaginary part	51-60	E
$I_{\ell i}(V_{\ell i})$	real part	61-70	E
	imaginary part	71-80	E

Note: A total of n cards must be present for an n wire line and must be arranged in the order:

wire 1

wire 2

.

.

.

wire n

TABLE 5

Group II(b) (total = n(n-1)/2 if OPTION = 12 or 22)
(total = 0 if OPTION = 11 or 21)

		card column	format
$Y_{0ij}(Z_{0ij})$	real part	1-10	E
	imaginary part	11-20	E
$Y_{\ell ij}(Z_{\ell ij})$	real part	41-50	E
	imaginary part	51-60	E

Note: If OPTION = 12 or 22, a total of n(n-1)/2 cards must be present and must follow Group II(a). If OPTION = 11 or 21, this card group is omitted. The cards must be arranged so as to describe the entries in the upper triangle portion of $\underset{\sim}{Y}_0(\underset{\sim}{Z}_0)$ and $\underset{\sim}{Y}_\ell(\underset{\sim}{Z}_\ell)$ by rows, i.e., the cards must contain the 12 entries, the 13 entries, ---, the 1n entries, the 23 entries, ---, the 2n entries, ---- etc. The ordering of the cards is therefore:

wires 1,2

wires 1,3

.

.

wires 1,n

wires 2,3

wires 2,4

.

.

wires 2,n

.

.

.

wires (n-1), n

One would have selected OPTION 11. The n=3 cards would be arranged (in this order)

Group II(a)

7.E0	8.E0	1.E0	2.E0	16.E0	0.E0	12.E0	0.E0
↑10	↑20	↑30	↑40	↑50	↑60	↑70	↑80
0.E0	9.E0	3.E0	5.E0	17.E0	18.E0	0.E0	13.E0
10.E0	11.E0	6.E0	4.E0	0.E0	19.E0	14.E0	15.E0

If the terminal impedance matrices were not diagonal, e.g., OPTION 12 is selected, then n(n-1)/2 additional cards, Group II(b), would follow the above n cards comprising Group II(a). These cards describe the entries in the upper triangle portion of the termination impedance or admittance matrices by rows. Suppose the networks are characterized by the same $\underline{V}_0$ and $\underline{V}_\mathcal{L}$ vectors as above but the $\mathbf{Z}_0$ and $\mathbf{Z}_\mathcal{L}$ matrices are

$$\mathbf{Z}_0 = \begin{bmatrix} 7 + j8 & 20 + j21 & 22 + j23 \\ 20 + j21 & j9 & 24 + j25 \\ 22 + j23 & 24 + j25 & 10 + j11 \end{bmatrix}$$

$$\mathbf{Z}_\mathcal{L} = \begin{bmatrix} 16 & 26 + j27 & 28 \\ 26 + j27 & 17 + j18 & j29 \\ 28 & j29 & j19 \end{bmatrix}$$

The following n(n-1)/2 = 3 cards must follow the above 3 cards in the order of the 12 entries first, the 13 entries next and then the 23 entries:

Group II(b)

20.E0	21.E0			26.E0	27.E0		
10	20			50	60		
22.E0	23.E0			28.E0	0.E0		
24.E0	25.E0			0.E0	29.E0		

4.3 Program XTALK

XTALK considers (n+1) conductor transmission lines consisting of n wires in a lossless, homogeneous surrounding medium and a reference conductor for the line voltages. The n wires and the reference conductor are considered to be perfect (lossless) conductors. There are three choices for the reference conductor type:

TYPE = 1: The reference conductor is a wire.

TYPE = 2: The reference conductor is an infinite ground plane.

TYPE = 3: The reference conductor is an overall cylindrical shield.

Cross-sectional views of each of these three structure types are shown in Figure 4-1, 4-2 and 4-3, respectively.

For the TYPE 1 structure shown in Figure 4-1, an arbitrary rectangular coordinate system is established with the center of the coordinate system at the center of the reference conductor. The radii of all (n+1) wires, r_{wi}, as well as the Z and Y coordinates of each of the n wires serve to completely describe the structure. Negative coordinate values must be input as negative data items. For example, Z_j and Y_j in Figure 4-1 would be negative numbers.

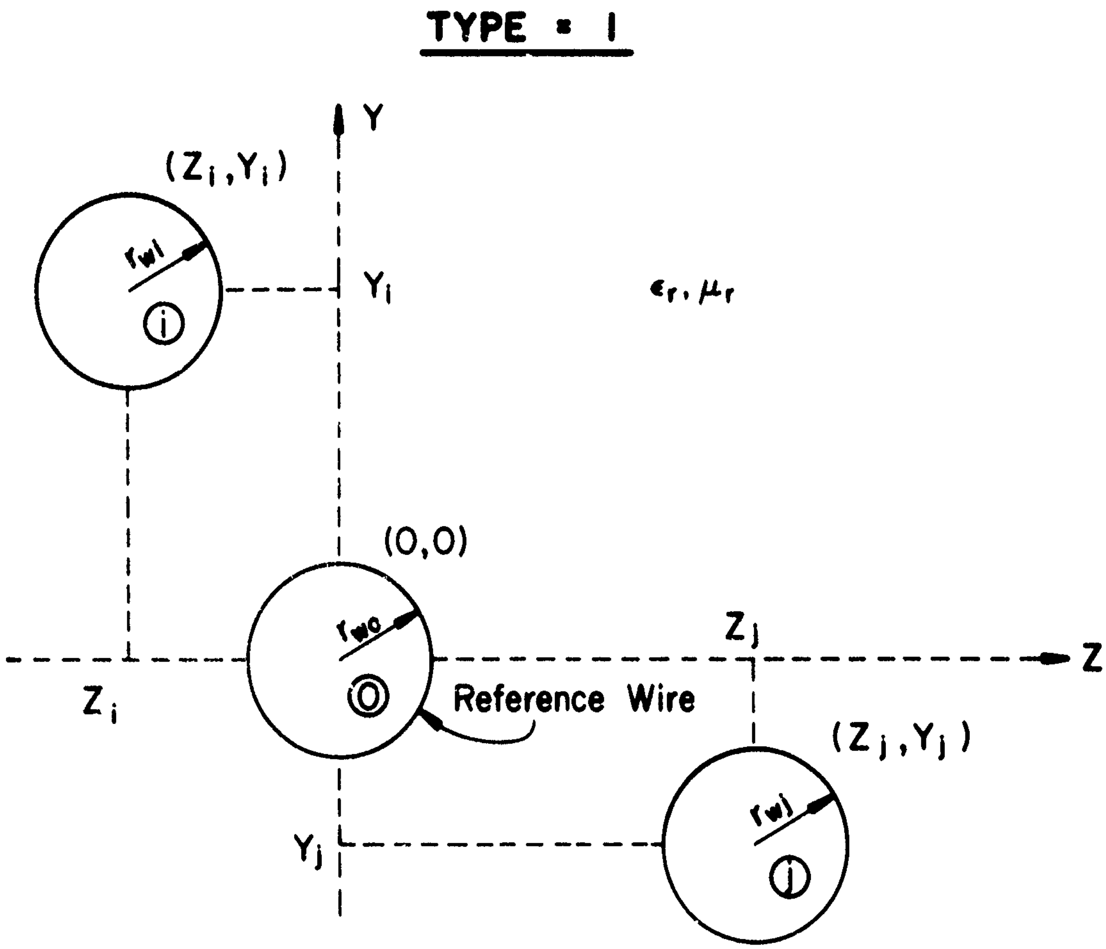


Figure 4-1. Type 1 structure.

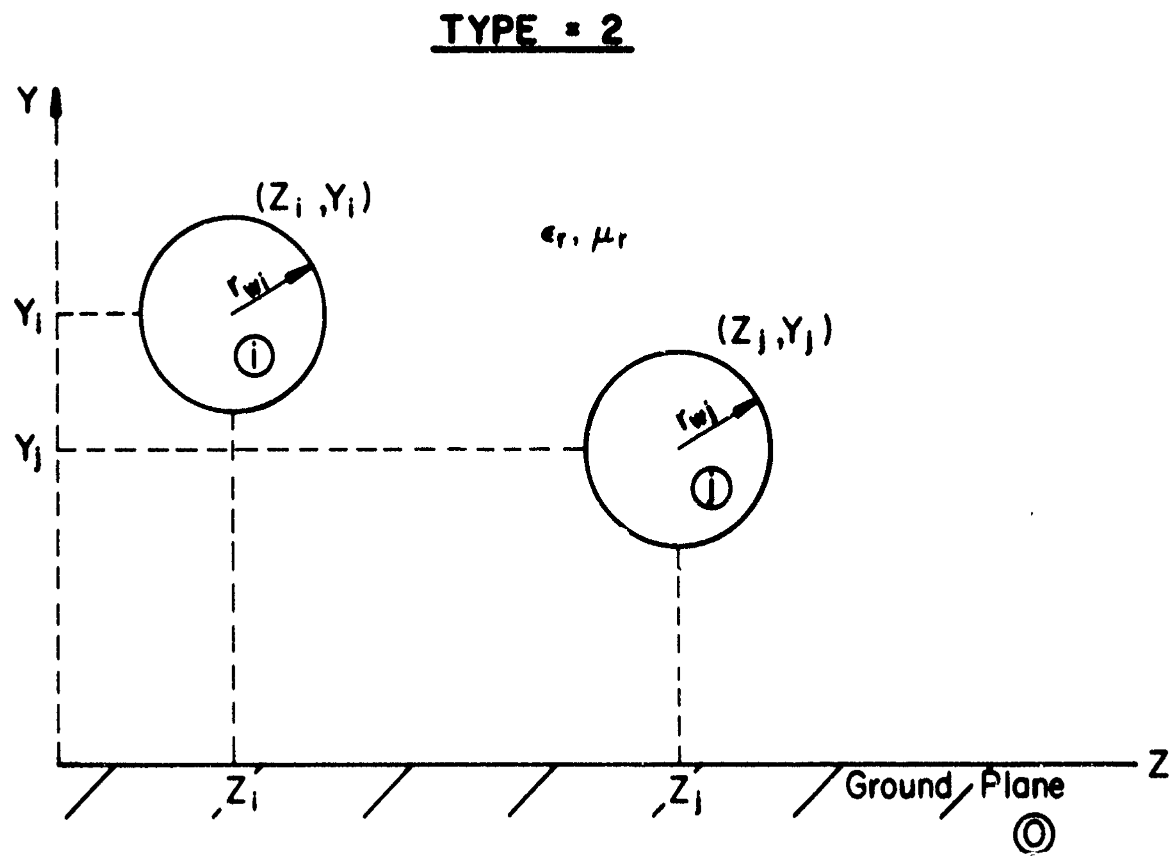


Figure 4-2. Type 2 structure.

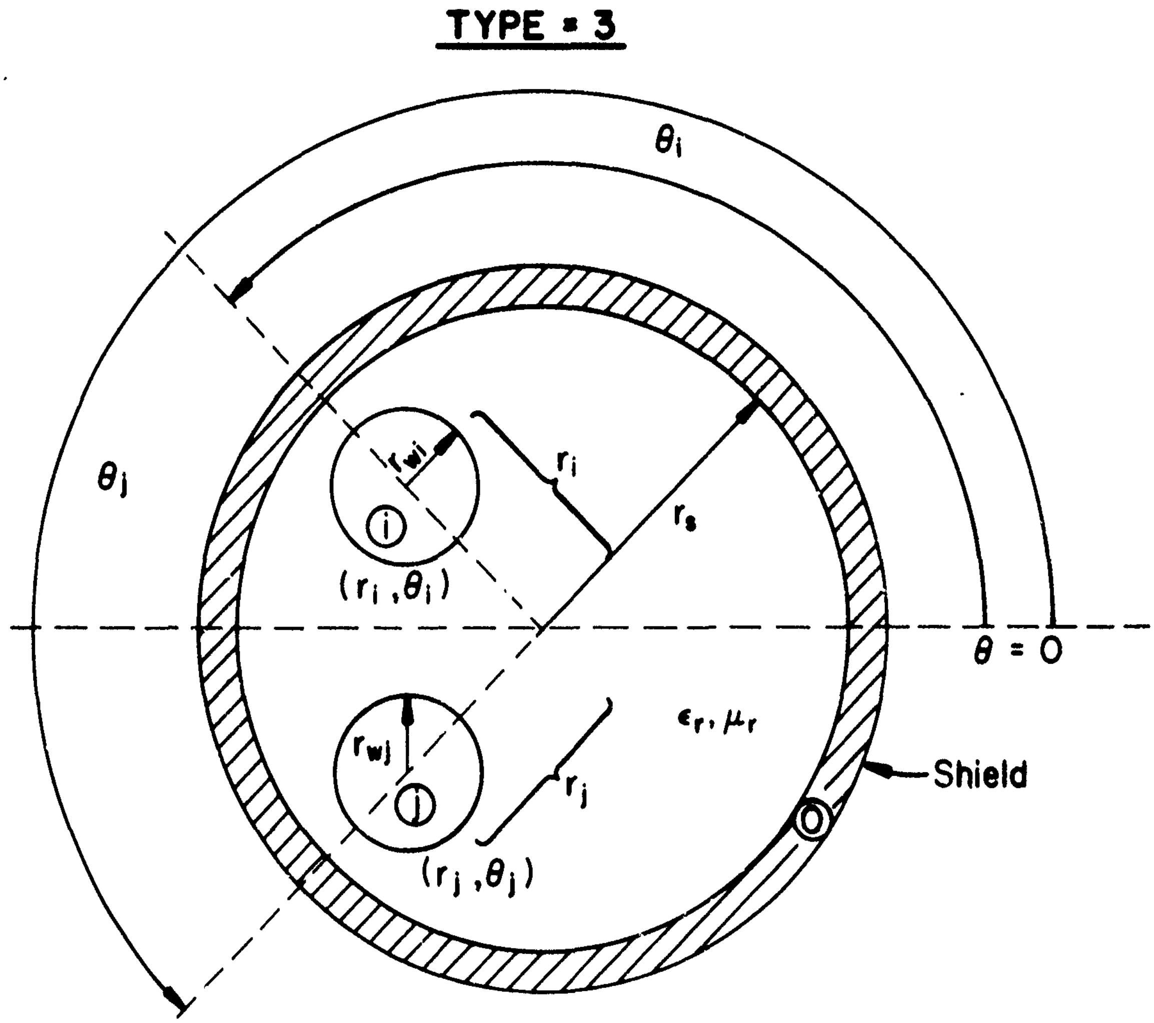


Figure 4-3. Type 3 structure.

For the TYPE 2 structure shown in Figure 4-2, an arbitrary coordinate system is established with the ground plane as the Z axis. The coordinates Y_i and Y_j (positive quantities) define the heights of the wires above the ground plane. The necessary data are the Z and Y coordinates and the radius, r_{wi}, of each wire.

For the TYPE 3 structure shown in Figure 4-3, an arbitrary angular coordinate system is established with the center of the coordinate system at the center of the shield. The necessary parameters are the radii of the wires, r_{wi}, the angular position, Θ_i, and the radial position, r_i, of each wire and the interior radius of the shield, r_s.

The format of the structural characteristics cards, Group I, are shown in TABLE 6. The first card contains the structure TYPE number (1,2,or 3), the load structure OPTION number (11,12,21, or 22), the number of wires, n, the relative dielectric constant of the surrounding medium (homogeneous), ε_r, the relative permeability of the surrounding medium (homogeneous), μ_r, and the total length of the transmission line, $\mathcal{L}$, (meters). If TYPE 1 or 3 is selected, a second card is required which contains the radius of the reference wire, r_{w0}, (mils) for TYPE 1 structures or the interior radius of the shield, r_s, (meters) for TYPE 3 structures. For TYPE 2 structures, this card is absent. These cards are followed by n cards each of which contain the radii of the wires, r_{wi}, (mils) and the Z_i and Y_i coordinates of each wire (meters) for TYPE 1 and 2 structures or the angular coordinates r_i (meters) and Θ_i (degrees) of the i-th wire for TYPE 3 structures. These n cards must be arranged in the order i = 1, i = 2, ---, i = n.

4.4 Program XTALK2

XTALK2 considers the same structure types as XTALK. The only difference between the programs is that XTALK2 considers imperfect conductors. This

TABLE 6

Format of the Structure Characteristics Cards, Group I, for XTALK

Card Group #1 (total = 1):	card column	format
(a) TYPE (1,2,3)	10	I
(b) LOAD STRUCTURE OPTION (11,12,21, or 22)	19 - 20	I
(c) n (number of wires)	29 - 30	I
(d) ε_r (relative dielectric constant of the surrounding medium)	36 - 45	E
(e) μ_r (relative permeability of the surrounding medium)	51 - 60	E
(f) $\mathcal{L}$ (line length in meters)	66 - 75	E
Card Group #2 (total = 1 if TYPE = 1 or 3; total = 0 if TYPE = 2)		
(a) TYPE = 1: r_{w0} (radius of reference wire in mils)	6 - 15	E
(b) TYPE = 2: absent		
(c) TYPE = 3: r_s (interior radius of shield in meters)	6 - 15	E
Card Group #3 (total = n)		
(a) r_{wi} (wire radius in mils)	6 - 15	E
(b) Z_i for TYPE 1 or 2 in meters; r_i for TYPE 3 in meters	21 - 30	E
(c) Y_i for TYPE 1 or 2 in meters; Θ_i for TYPE 3 in degrees	36 - 45	E

Note: Cards in Group #3 must be arranged in the order:

wire 1
wire 2
.
.
wire n

requires an additional set of cards in Group I which must follow those in Table 6. The format of these cards is shown in Table 7.

4.5 Program FLATPAK

FLATPAK considers (n+1) wire flatpak or ribbon cables as shown in Figure 4-4. The (n+1) wires are considered to be perfect conductors. In addition,the surrounding media are assumed to be lossless. The required cards in the Structure Characteristics card group, Group I, are shown in Table 8.

The first card is similar to the previous programs and communicates three items to the program. The first entry on the card is the number n which is the number of wires in the cable exclusive of the reference wire. The second entry on the card is the load structure option which is to be selected from the choices 11, 12, 21, or 22 as discussed in section 3.2. The third entry on this card is the total length of the cable in meters.

Card Group 2 concerns the entries in the per-unit-length capacitance matrix, $\underset{\sim}{C}$, for the ribbon cable. Since $\underset{\sim}{C}$ is symmetric, it is only necessary to input the entries on the main diagonal of $\underset{\sim}{C}$ and the entries in the upper (or lower) triangle of $\underset{\sim}{C}$. Computer program GETCAP [8] was designed to compute these items. GETCAP has the provision for providing a punched card output of the entries in $\underset{\sim}{C}$ in the form required by FLATPAK.

A few comments are in order to assist users of GETCAP. The program is documented in Volume II of this series [8]. However, some confusion as to the wire numbering sequence in GETCAP and FLATPAK may arise. The wires in the cable are numbered from left to right with numbers from 1 to N=n+1 for use in the GETCAP program with the reference wire number chosen from this sequence. In the FLATPAK program, the wires are numbered from left to

TABLE 7 (Cont.)

Format of the Structure Characteristics Cards, Group I, for XTALK 2

Card Group #1 — same as XTALK (TABLE 6)

Card Group #2 — same as XTALK (TABLE 6)

Card Group #3 — same as XTALK (TABLE 6)

Card Group #4 (total = 1)		card column	format
TYPE = 1:	(a) radius of strands in reference wire (mils)	6 - 15	E
	(b) conductivity of strands (siemens/meter)	21 - 30	E
	(c) number of strands in reference wire	39 - 40	I
TYPE = 2:	(a) per-unit-length resistance of ground plane (ohms/meter)	6 - 15	E
	(b) per-unit-length inductance of ground plane (henrys/meter)	21 - 30	E
TYPE = 3:	(a) thickness of shield (meters)	6 - 15	E
	(b) conductivity of shield (siemens/meter)	21 - 30	E

Card Group # 5 (total = n)	card column	format
(a) radius of wire strands (mils)	6 - 15	E
(b) conductivity of wire strands (siemens/meter)	21 - 30	E
(c) number of strands in wire	39 - 40	I

NOTE: Cards in Group #5 must be arranged for wires from 1 to n.

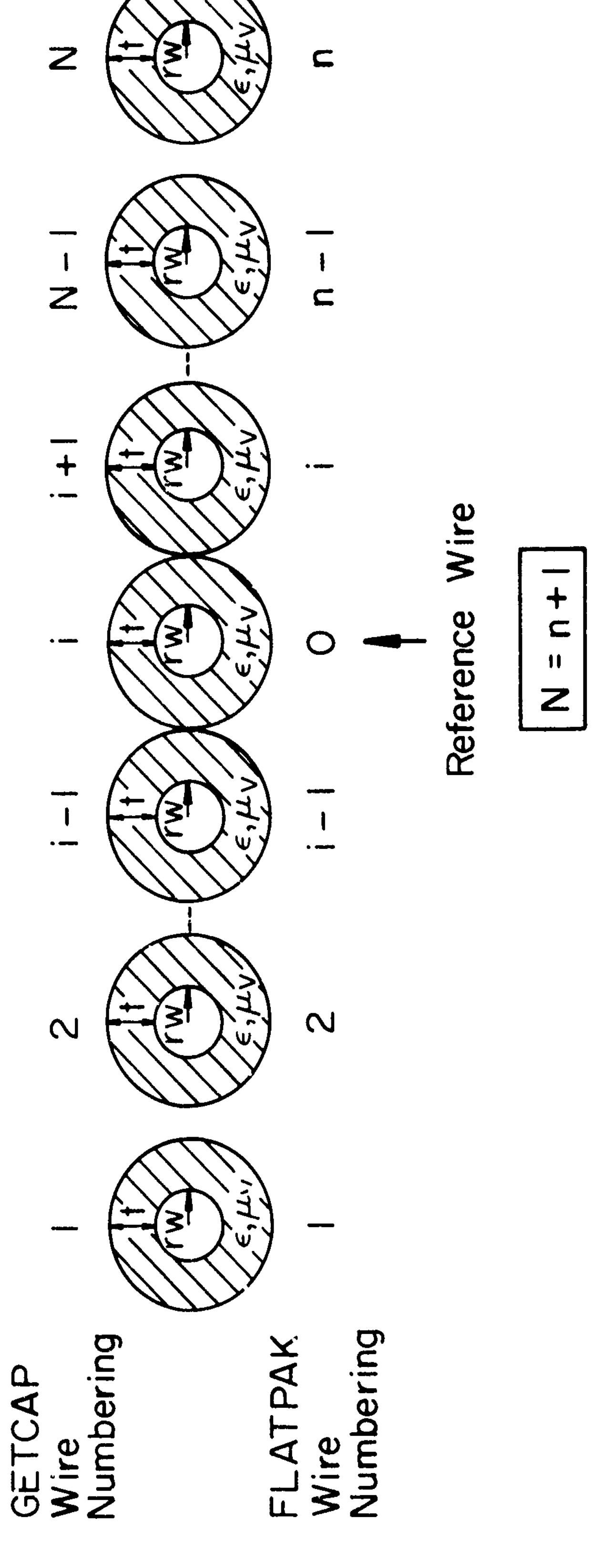


Figure 4-4. Wire numbering for ribbon (flatpack) cables.

TABLE 8

Format of the Structure Characteristics Cards, Group I, for FLATPAK

Card Group #1 (total = 1)	Card Column	Format
(a) Number of wires (exclusive of the reference wire) (n)	9 - 10	I
(b) LOAD STRUCTURE OPTION (11,12,21, or 22)	19 - 20	I
(c) Line length (meters) $\mathcal{L}$	21 - 30	E

Card Group #2 (total = n(n+1)/2)	Card Column	Format
(a) i	5 - 6	I
(b) j	10 - 11	I
(c) $[\underset{\sim}{C}]_{ij}$ (farads/meter) (Entries in the per-unit-length transmission line capacitance matrix with the wire dielectric insulations in place, computed with GETCAP)	14 - 26	E

Card Group #3 (total = n(n+1)/2)	Card Column	Format
(a) i	5 - 6	I
(b) j	10 - 11	I
(c) $[\underset{\sim}{C}_0]_{ij}$ (farads/meter) (Entries in the per-unit-length transmission line capacitance matrix with the wire dielectric insulations removed, computed with GETCAP)	14 - 26	E

right with numbers from 1 to n with the reference wire numbered as the zero (0) wire as shown in Figure 4-4. Whether the cross section of the cable in Figure 4-4 is at x=0 looking to the right (increasing x) or at $x = \mathcal{L}$ looking to the left (decreasing x) is irrelevant so long as the user is consistent in using the same cross section for wire numbering in GETCAP and in this program when assigning the load termination entries.

The third group of cards in Group I, Card Group #3, are the elements of the per-unit-length transmission line capacitance matrix computed <u>with the dielectric insulations removed</u>, $\underset{\sim}{C}_0$. GETCAP may be used to compute these items and provide punched card output for direct use as data input for FLATPAK.

4.6 Program FLATPAK 2

FLATPAK 2 considers (n+1) wire ribbon cables as in FLATPAK. However, FLATPAK 2 considers the (n+1) wires to be imperfect (lossy) conductors.

The format of the Structure Characteristic Cards, Group I, is shown in TABLE 9. Only one additional card over those required for FLATPAK is needed. Since all wires in the cable are assumed to be identical, this card describes the characteristics of these wires for use in computing the wire self impedances.

4.7 Examples of Program Useage

In this section, some typical examples will be shown to illustrate the use of the programs. Entries on the data cards as well as typical printouts of the results will be shown.

The terminal network structures for the examples are those comprising Examples 1, 2, 3, and 4 shown in Figure 2-4 and Figure 2-5. For Examples

TABLE 9

Format of the Structure Characteristics Cards, Group I, for FLATPAK 2

		Card Column	Format
Card Group #1	same as FLATPAK		
Card Group #2	same as FLATPAK		
Card Group #3	same as FLATPAK		
Card Group #4	(total = 1)		
(a)	radius of wire strands (mils)	6 - 15	E
(b)	conductivity of wire strands (siemens/meter)	21 - 30	E
(c)	number of strands in each wire	39 - 40	I

1 and 2, the entries in the Thevenin Equivalent characterization matrices are given in (2-32) and the entries in the Norton Equivalent characterization matrices are given in (2-35). For Examples 3 and 4, the entries in the Norton Equivalent characterization matrices are given in (2-37) and the entries in the Thevenin Equivalent characterization matrices are given in (2-38).

The terminal voltages for each wire (with respect to the reference conductor) at x=0 and x=$\mathcal{L}$ are the entries in $\underline{V}(0)$ and $\underline{V}(\mathcal{L})$, respectively. The magnitudes and angles of the entries in $\underline{V}(0)$ ($\underline{V}(\mathcal{L})$) are denoted by VOM and VOA (VLM and VLA), respectively, on the computer printouts. Two frequencies will be considered, 10 MHz and 100 MHz.

4.7.1 Examples of the XTALK Program

The transmission line structure chosen for all examples in this section is that of two wires with another wire as the reference conductor. The wire radii (mils) are 6.3 mils (thousands of a inch) for wires #1 and #2 with the reference wire of radius 6.3 mils. The three wires are in a linear array with Z_1 = 1.27 mm, Y_1 = 0, Z_2 = 2.54 mm, Y_2 = 0. The line length is 5 meters and the relative dielectric constant is chosen (for the purpose of illustration) to be 3.0 with a relative permeability of 1.0.

The data cards are shown in Figure 4-5 through 4-8 and the printouts are shown in Figure 4-9 through 4-12.

4.7.2 Examples of the XTALK 2 Program

The line considered for XTALK in 4.7.1 will be used here. Each wire will be stranded, copper ($\sigma = 5.8 \times 10^7$) with 7 strands in each wire. The radius of each strand is 2.5 mils.

The data cards are shown in Figure 4-13 through 4-16 and the printouts are shown in Figure 4-17 through 4-20.

4.7.3 Examples of the FLATPAK Program

A three wire ribbon cable will be considered. The wire radii are .16002 mm, the insulation thicknesses are .3479 mm and the center-to-center separations of the wires are 1.27 mm. The insulations are polyvinyl chloride and a relative dielectric constant of 3.5 is assumed. The reference wire is the middle wire in the cable. The elements in the per-unit-length capacitance matrix (with and without the dielectric insulations) were computed with GETCAP [8].

The data cards are shown in Figure 4-21 through 4-24 and the printouts are shown in Figure 4-25 through 4-28.

4.7.4 Examples of the FLATPAK 2 Program

The three wire ribbon cable considered in the previous section with the FLATPAK program will be investigated. Each wire is stranded with 7 strands (copper) and each strand is of radius 2.5 mils.

The data cards are shown in Figure 4-29 through 4-32 and the printouts are shown in Figure 4-33 through 4-36.

```
      1.E8
      1.E7
     1.0E1     0.0E0     0.0E0     0.0E0     1.0E4     0.0E0     1.0E0     0.0E0
     1.0E0     0.0E0     1.0E0     0.0E0     1.0E3     0.0E0     0.0E0     0.0E0
          6.3E0          2.54E-3             0.0E0
          6.3E0          1.27E-3             0.0E0
          6.3E0
          1         11        2          3.0E0          1.0E0          5.0E0
```

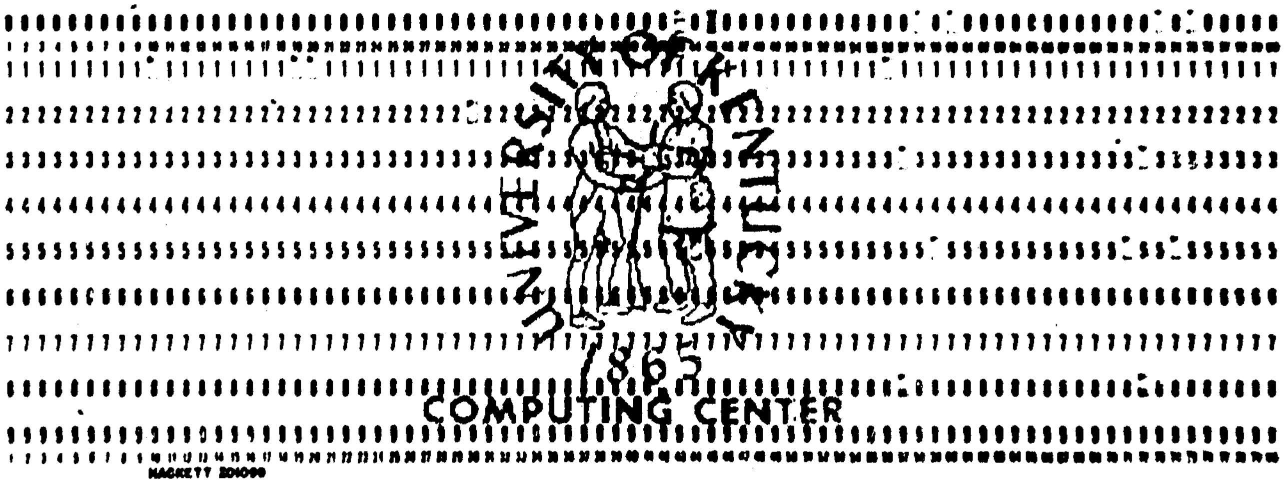


Figure 4-5. Input Cards, XTALK, Example 1.

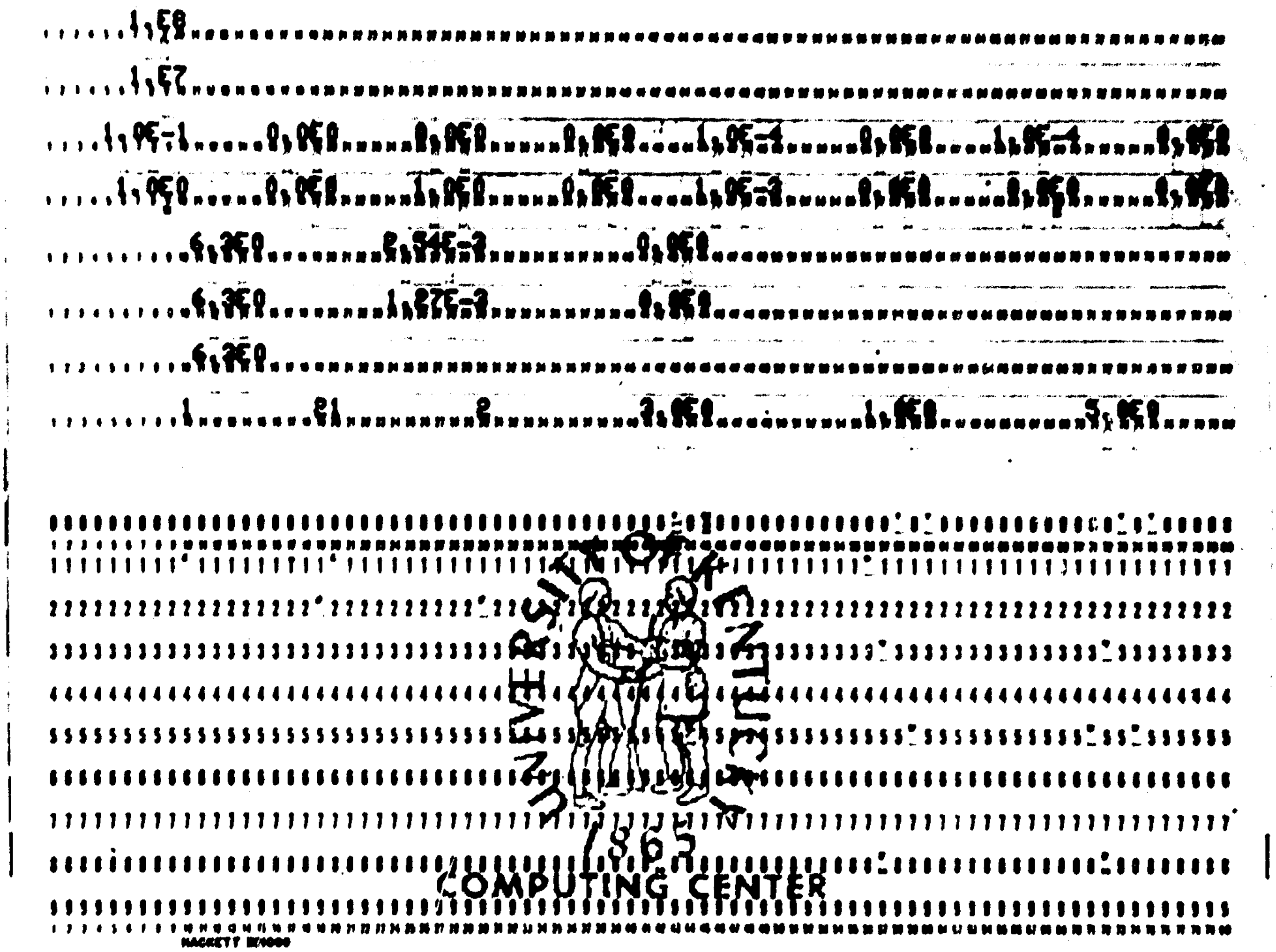


Figure 4-6. Input Cards, XTALK, Example 2.

```
      1.E8
      1.E7
    2.0E0     0.0E0                              1.0E0     0.0E0
    3.0E0     0.0E0     2.0E0     0.0E0     3.0E0     0.0E0     2.0E0     0.0E0
    3.0E0     5.0E0     2.0E0     0.0E0     2.0E0     0.0E0     1.0E0     0.0E0
          6.3E0          2.54E-2              0.0E0
          6.3E0          1.27E-3              0.0E0
          6.3E0
         1         18         2              3.0E0          1.0E0          5.0E0
```

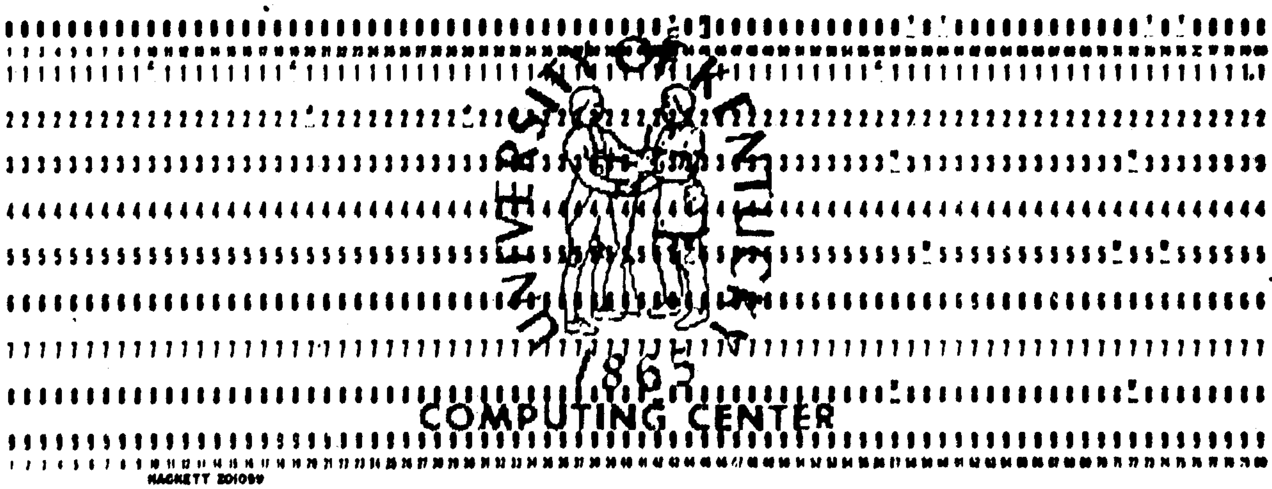
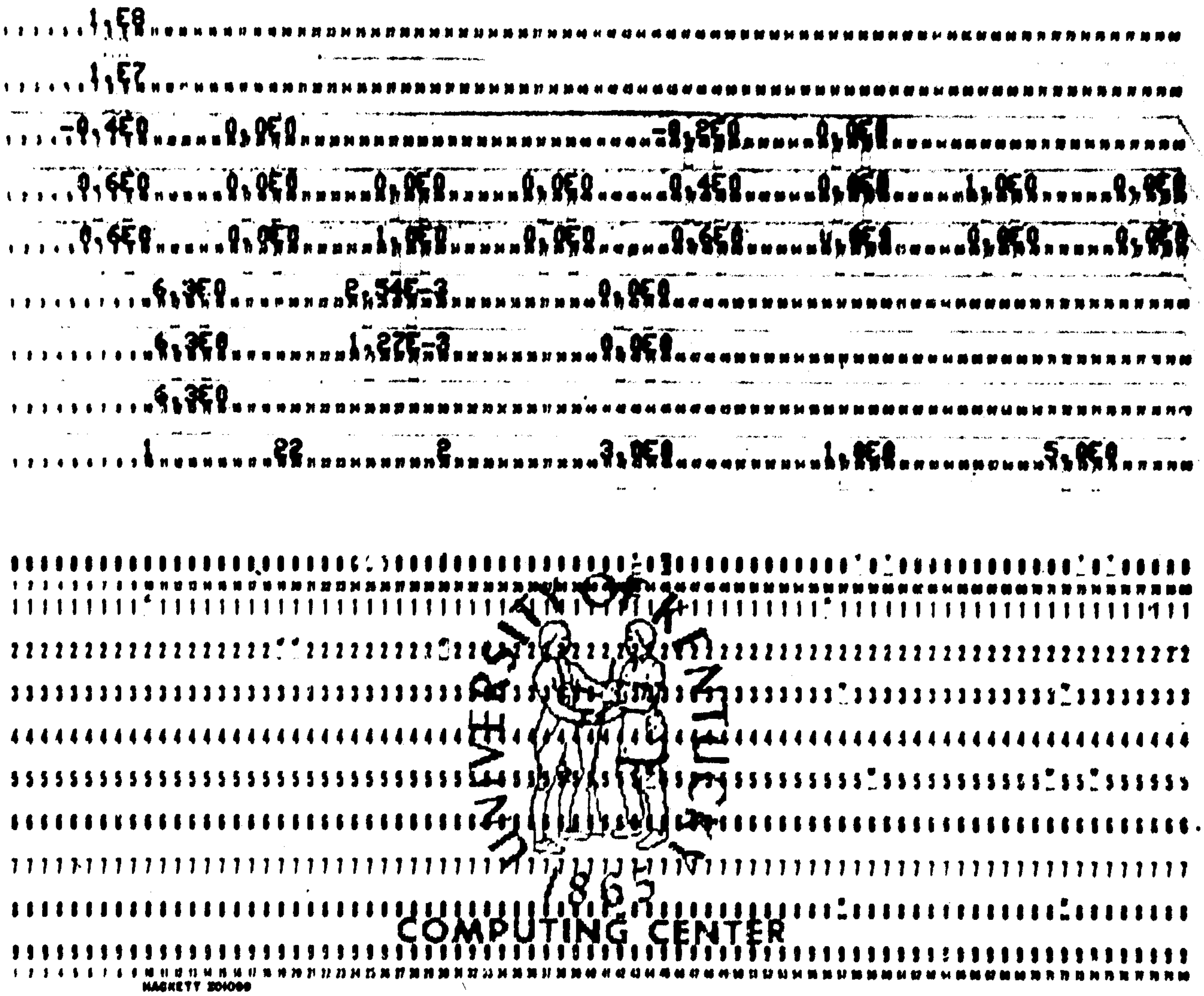


Figure 4-7. Input Cards, XTALK, Example 3.



```
      1.E8
      1.E7
    -0.4E0     0.0E0                              -0.2E0     0.0E0
     0.6E0     0.0E0     0.0E0     0.0E0     0.4E0     0.0E0     1.0E0     0.0E0
     0.6E0     0.0E0     1.0E0     0.0E0     0.6E0     0.0E0     0.0E0     0.0E0
          6.3E0          2.54E-3             0.0E0
          6.3E0          1.27E-3             0.0E0
          6.3E0
          1         22         2              3.0E0              1.0E0               5.0E0
```


Figure 4-8. Input Cards, XTALK, Example 4.

```
                                   XTALK
                             2 PARALLEL WIRES
                          TYPE OF STRUCTURE= 1
                        LOAD STRUCTURE OPTION= 11
                   LINE LENGTH=  5.0000000D 00 METERS
             DIELECTRIC CONSTANT OF THE MEDIUM=  3.0000 00
            RELATIVE PERMEABILITY OF THE MEDIUM=  1.0000 00

REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A WIRE WITH RADIUS=  6.3000 00 MILS

WIRE NUMBER   WIRE RADIUS (MILS)        Z COORDINATE (METERS)        Y COORDINATE (METERS)
   1            6.3000 00                  1.2700-03                    0.0000-01
   2            6.3000 00                  2.5400-03                    0.0000-01

             IMPEDANCE AT X=0       VOLTAGE SOURCE AT X=0       IMPEDANCE AT X=L       VOLTAGE SOURCE AT X=L
                  (OHMS)                  (VOLTS)                    (OHMS)                  (VOLTS)
ENTRY          REAL       IMAG         REAL       IMAG          REAL       IMAG         REAL       IMAG
 1  1       1.0000 00  0.0000-01    1.0000 00  0.0000-01     1.0000 03  0.0000-01    3.0000-01  0.0000-01
 2  2       1.0000 01  0.0000-01    0.0000-01  0.0000-01     1.0000 04  0.0000-01    1.6000 00  0.0000-01

CHARACTERISTIC IMPEDANCE MATRIX INVERSION ERROR=  0


  FREQUENCY(HERTZ)=  1.00000 07          SOLUTION ERROR=     0

                WIRE        VOM(VOLTS)   VOA(DEGREES)       VLM(VOLTS)   VLA(DEGREES)
                 1          9.8290-01    1.8770 00          3.51[illegible] 00   -1.4790 02
                 2          1.9940-01   -7.1360 01          6.3[illegible]0-01   -3.9940 01


  FREQUENCY(HERTZ)=  1.00000 08          SOLUTION ERROR=     0

                WIRE        VOM(VOLTS)   VOA(DEGREES)       VLM(VOLTS)   VLA(DEGREES)
                 1          9.9810-01    4.9100-01          1.2940 00    7.0090 00
                 2          4.3870-02   -8.4920 01          3.0990-02    1.0350 02

 CORE USAGE      OBJECT CODE=   20336 BYTES,ARRAY AREA=     672 BYTES,TOTAL AREA AVAILABLE=  161792  BYTES
 DIAGNOSTICS        NUMBER OF ERRORS=       0, NUMBER OF WARNINGS=       0, NUMBER OF EXTENSIONS=       3
 COMPILE TIME=    0.54 SEC,EXECUTION TIME=     0.06 SEC,     10.44.45    TUESDAY       4 OCT 77    WATFIV - JAN 1976 V1L6
```

Figure 4-9. Output Listing, XTALK, Example 1.

```
                                   XTALK
                              2 PARALLEL WIRES
                             TYPE OF STRUCTURE= 1
                           LOAD STRUCTURE OPTION= 21
                       LINE LENGTH=  5.0000000D 00 METERS
                  DIELECTRIC CONSTANT OF THE MEDIUM=  3.0000 00
                RELATIVE PERMEABILITY OF THE MEDIUM=  1.0000 00

REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A WIRE WITH RADIUS=  6.3000 00 MILS

WIRE NUMBER    WIRE RADIUS (MILS)          Z COORDINATE (METERS)              Y COORDINATE (METERS)
  1              6.3000 00                    1.2700-03                          0.0000-01
  2              6.3000 00                    2.5400-03                          0.0000-01

              ADMITTANCE AT X=0       CURRENT SOURCE AT X=0        ADMITTANCE AT X=L       CURRENT SOURCE AT X=L
                 (SIEMENS)                   (AMPS)                   (SIEMENS)                 (AMPS)
ENTRY          REAL        IMAG        REAL        IMAG         REAL        IMAG         REAL        IMAG
 1   1      1.0000 00   0.0000-01   1.0000 00   0.0000-01    1.0000-03   0.0000-01    0.0000-01   0.0000-01
 2   2      1.0000-01   0.0000 01   0.0000-01   0.0000-01    1.0000-04   0.0000-01    1.0000-04   0.0000-01

CHARACTERISTIC IMPEDANCE MATRIX INVERSION ERROR=  0


  FREQUENCY(HERTZ)=  1.0000D 07         SOLUTION ERROR=    0

                  WIRE        VOM(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)
                   1          9.8290-01    1.0770 00           3.5100 00    -1.4790 02
                   2          1.9840-01    -7.1250 01          6.3060-01    -3.9940 01


  FREQUENCY(HERTZ)=  1.0000D 08         SOLUTION ERROR=    0

                  WIRE        VOM(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)
                   1          9.9810-01    4.9100-01           1.2940 00    [illegible] 00
                   2          4.3870-02    -8.4020 01          3.0990-02    1.02[illegible] 02

CORE USAGE       OBJECT CODE=   20336 BYTES,ARRAY AREA=     672 BYTES,TOTAL AREA AVAILABLE=  161792  BYTES
DIAGNOSTICS        NUMBER OF ERRORS=       0, NUMBER OF WARNINGS=       0, NUMBER OF EXTENSIONS=       3
COMPILE TIME=    0.63 SEC,EXECUTION TIME=     0.07 SEC,     10.42.11     TUESDAY        4 OCT 77    WATFIV - JAN 1976 V1L5

         $STOP
```

Figure 4-10. Output Listing, XTALK, Example 2.

```
                                        XTALK
                                  2 PARALLEL WIRES
                                 TYPE OF STRUCTURE= 1
                               LOAD STRUCTURE OPTION= 12
                          LINE LENGTH=  5.0000000D 00 METERS
                     DIELECTRIC CONSTANT OF THE MEDIUM=  3.0000 00
                    RELATIVE PERMEABILITY OF THE MEDIUM=  1.0000 00

REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A WIRE WITH RADIUS=  6.3000 00 MILS

WIRE NUMBER    WIRE RADIUS (MILS)           Z COORDINATE (METERS)              Y COORDINATE (METERS)
   1              6.3000 00                      1.2700-03                          0.0000-01
   2              6.3000 00                      2.5400-03                          0.0000-01

                  IMPEDANCE AT X=0         VOLTAGE SOURCE AT X=0         IMPEDANCE AT X=L        VOLTAGE SOURCE AT X=L
                      (OHMS)                     (VOLTS)                     (OHMS)                    (VOLTS)
ENTRY            REAL          IMAG          REAL          IMAG          REAL          IMAG          REAL          IMAG
 1  1         3.0000 00     0.0000-01     3.0000 00     0.0000-01     2.0000 00     0.0000-01     1.0000 00     0.0000-01
 2  2         3.0000 00     0.0000-01     2.0000 00     0.0000-01     3.0000 00     0.0000-01     3.0000 00     0.0000-01
 1  2         2.0000 00     0.0000-01                                 1.0000 00     0.0000-01

CHARACTERISTIC IMPEDANCE MATRIX INVERSION ERROR=  0


  FREQUENCY(HERTZ)=  1.0000D 07          SOLUTION ERROR=    0

               WIRE        VOM(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)
                 1         2.9990 00    -7.0960-01          1.0000 00    -2.5810 00
                 2         2.0000 00    -1.6090 00          2.9990 00    -6.4720-01


  FREQUENCY(HERTZ)=  1.0000D 08          SOLUTION ERROR=    0

               WIRE        VOM(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)
                 1         2.9970 00    -8.0390-01          1.0040 00     3.1780 00
                 2         2.0000 00     5.2120-01          2.9980 00    -5.0670-01

CORE USAGE       OBJECT CODE=   20336 BYTES,ARRAY AREA=     672 BYTES,TOTAL AREA AVAILABLE=  161792  BYTES
DIAGNOSTICS        NUMBER OF ERRORS=        0, NUMBER OF WARNINGS=        0, NUMBER OF EXTENSIONS=        3
COMPILE TIME=     0.55 SEC,EXECUTION TIME=     0.06 SEC,     10.40.27     TUESDAY        4 OCT 77     WATFIV - JAN 1976 V1L5

        $STOP
```

Figure 4-11. Output Listing, XTALK, Example 3.

```
                                          XTALK

                                    2 PARALLEL WIRES

                                  TYPE OF STRUCTURE= 1

                                 LOAD STRUCTURE OPTION= 22

                             LINE LENGTH=  5.0000000 00 METERS

                        DIELECTRIC CONSTANT OF THE MEDIUM=  3.0000 00

                       RELATIVE PERMEABILITY OF THE MEDIUM=  1.0000 00

  REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A WIRE WITH RADIUS=  6.3000 00 MILS

  WIRE NUMBER    WIRE RADIUS (MILS)              Z COORDINATE (METERS)                  Y COORDINATE (METERS)

    1             6.3000 00                        1.270D-03                              0.0000D-01
    2             6.3000 00                        2.540D-03                              0.0000D-01

                 ADMITTANCE AT X=0          CURRENT SOURCE AT X=0          ADMITTANCE AT X=L          CURRENT SOURCE AT X=L
                     (SIEMENS)                      (AMPS)                      (SIEMENS)                      (AMPS)
  ENTRY            REAL          IMAG          REAL          IMAG          REAL          IMAG          REAL          IMAG

  1   1       6.0000D-01    0.0000D-01    1.0000 00     0.0000D-01    6.0000D-01    0.0000D-01    0.0000D-01    0.0000D-01
  2   2       6.0000D-01    0.0000D-01    0.0000D-01    0.0000D-01    4.0000D-01    0.0000D-01    1.0000 00     0.0000D-01
  1   2      -6.0000D-01    0.0000D-01                                 -2.0000D-01    0.0000D-01

  CHARACTERISTIC IMPEDANCE MATRIX INVERSION ERROR=  0


    FREQUENCY(HERTZ)=  1.00000 07          SOLUTION ERROR=    0

                 WIRE        VON(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)

                  1          2.999D 00   -7.096D-01           1.000D 00    -2.881D 00
                  2          2.000D 00   -1.609D 00           2.999D 00    -6.472D-01


    FREQUENCY(HERTZ)=  1.00000 08          SOLUTION ERROR=    0

                 WIRE        VON(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)

                  1          2.997D 00   -6.039D-01           1.004D 00     3.179D 00
                  2          2.000D 00    9.519D-01           2.999D 00    -5.967D-01

  CORE USAGE        OBJECT CODE=   20336 BYTES,ARRAY AREA=     672 BYTES,TOTAL AREA AVAILABLE=  161792  BYTES
  DIAGNOSTICS         NUMBER OF ERRORS=       0, NUMBER OF WARNINGS=       0, NUMBER OF EXTENSIONS=       3
  COMPILE TIME=     0.60 SEC,EXECUTION TIME=     0.06 SEC,     10.41.28    TUESDAY        4 OCT 77    WATFIV - JAN 1976 V1L5

          $STOP
```

Figure 4-12. Output Listing, XTALK, Example 4.

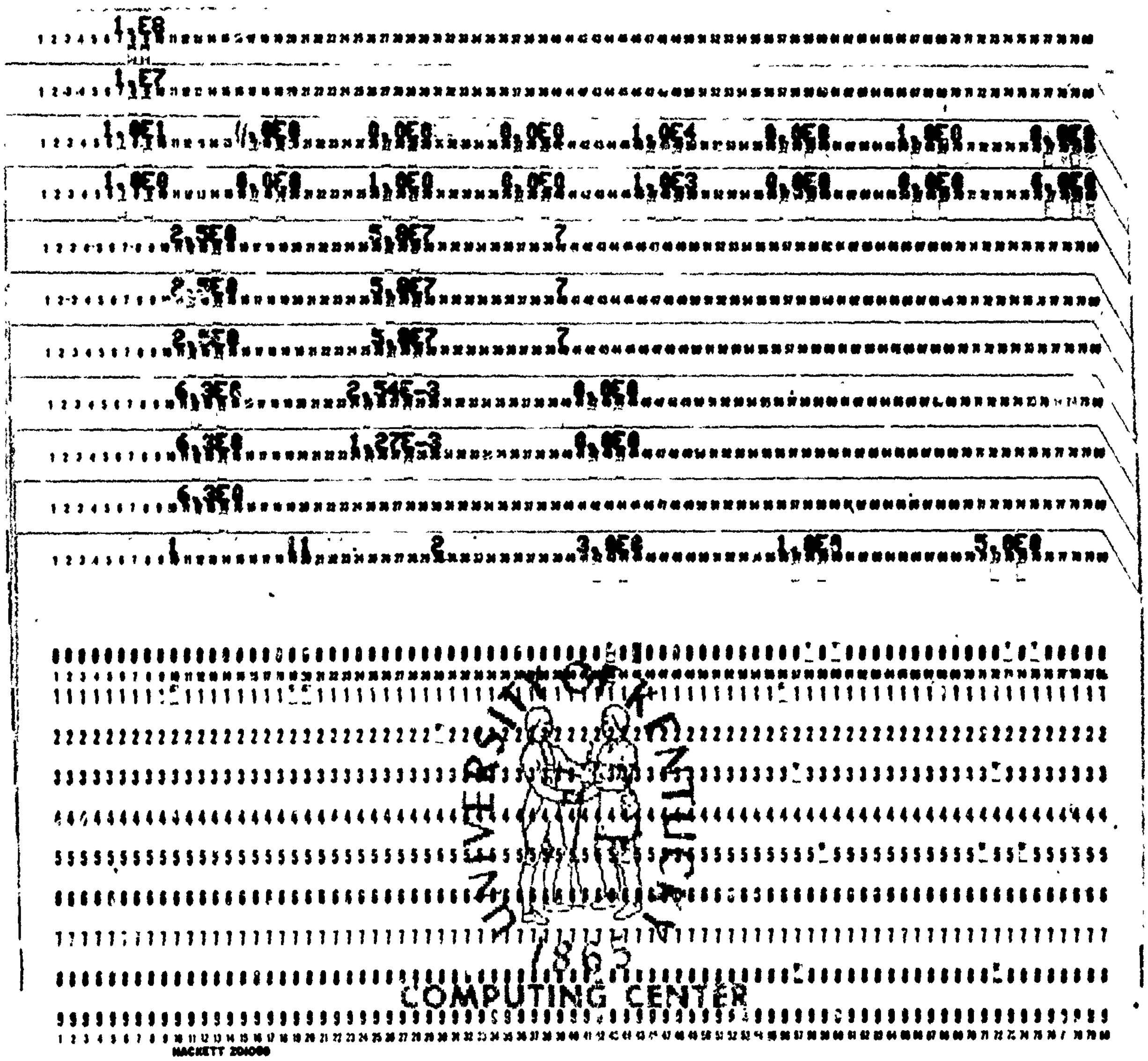
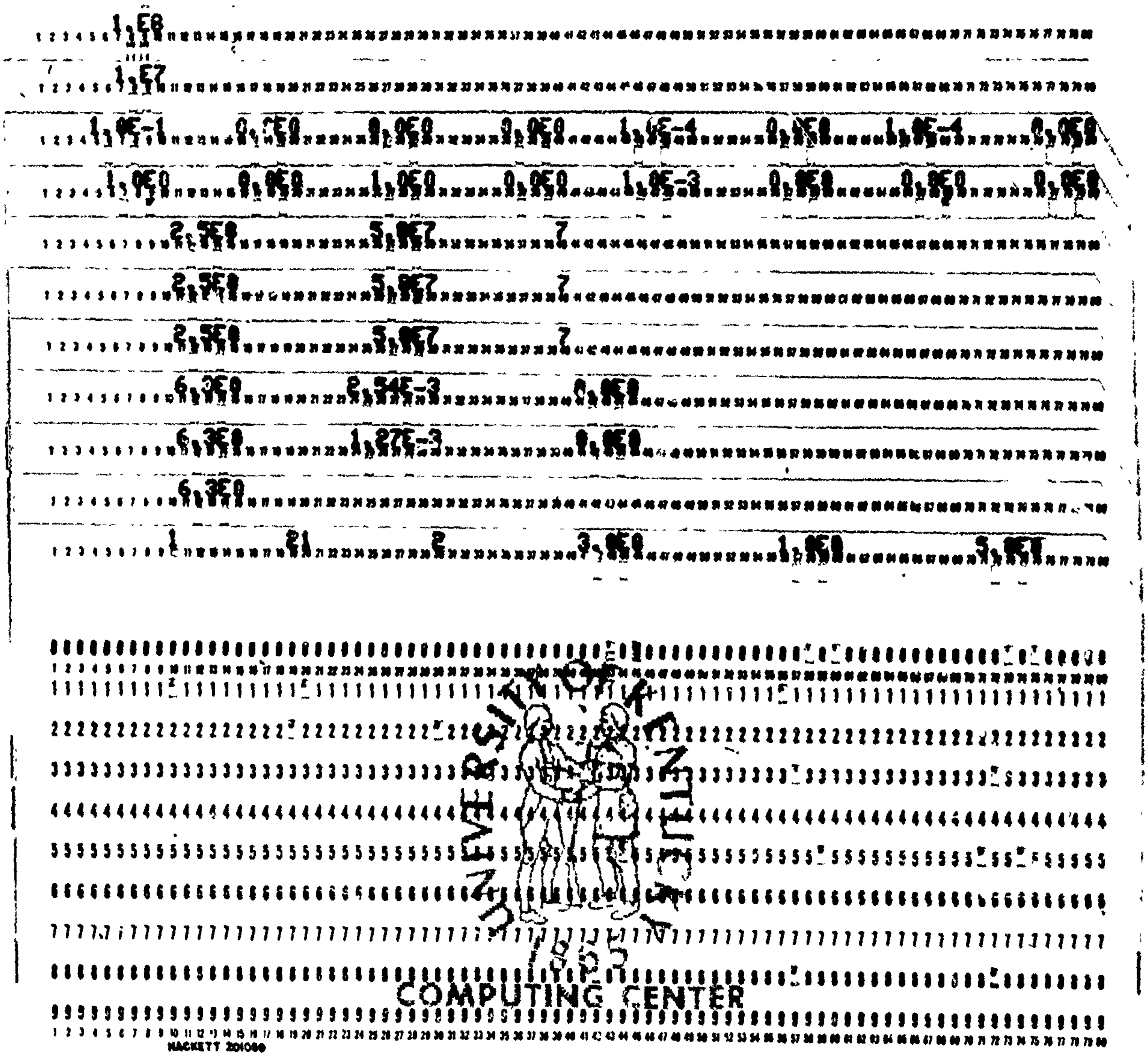


Figure 4-13. Input Cards, XTALK2, Example 1.



BEST AVAILABLE COPY

Figure 4.14. Input Cards, XTALK2, Example 2.

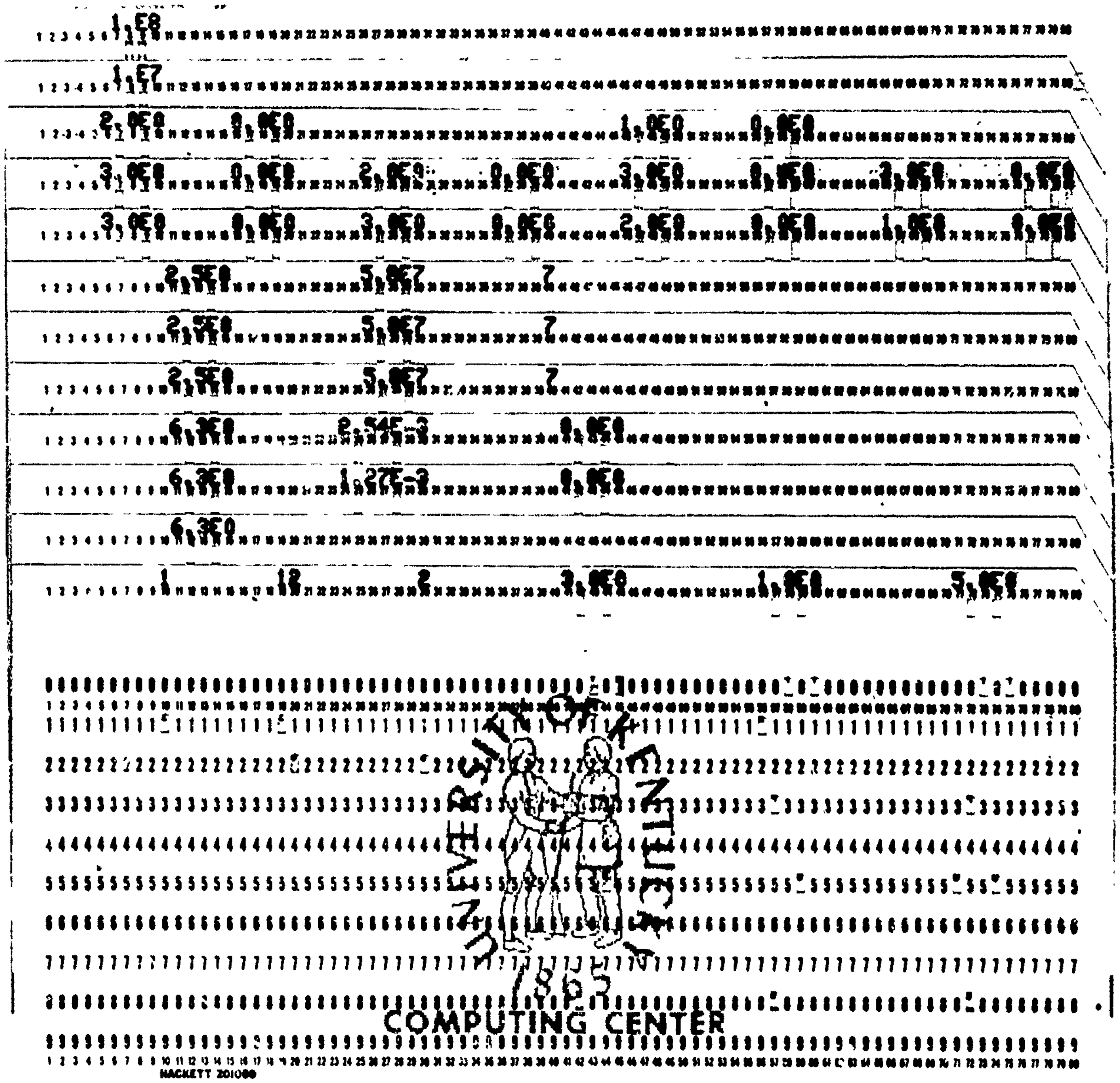


Figure 4-15. Input Cards, XTALK2, Example 3.

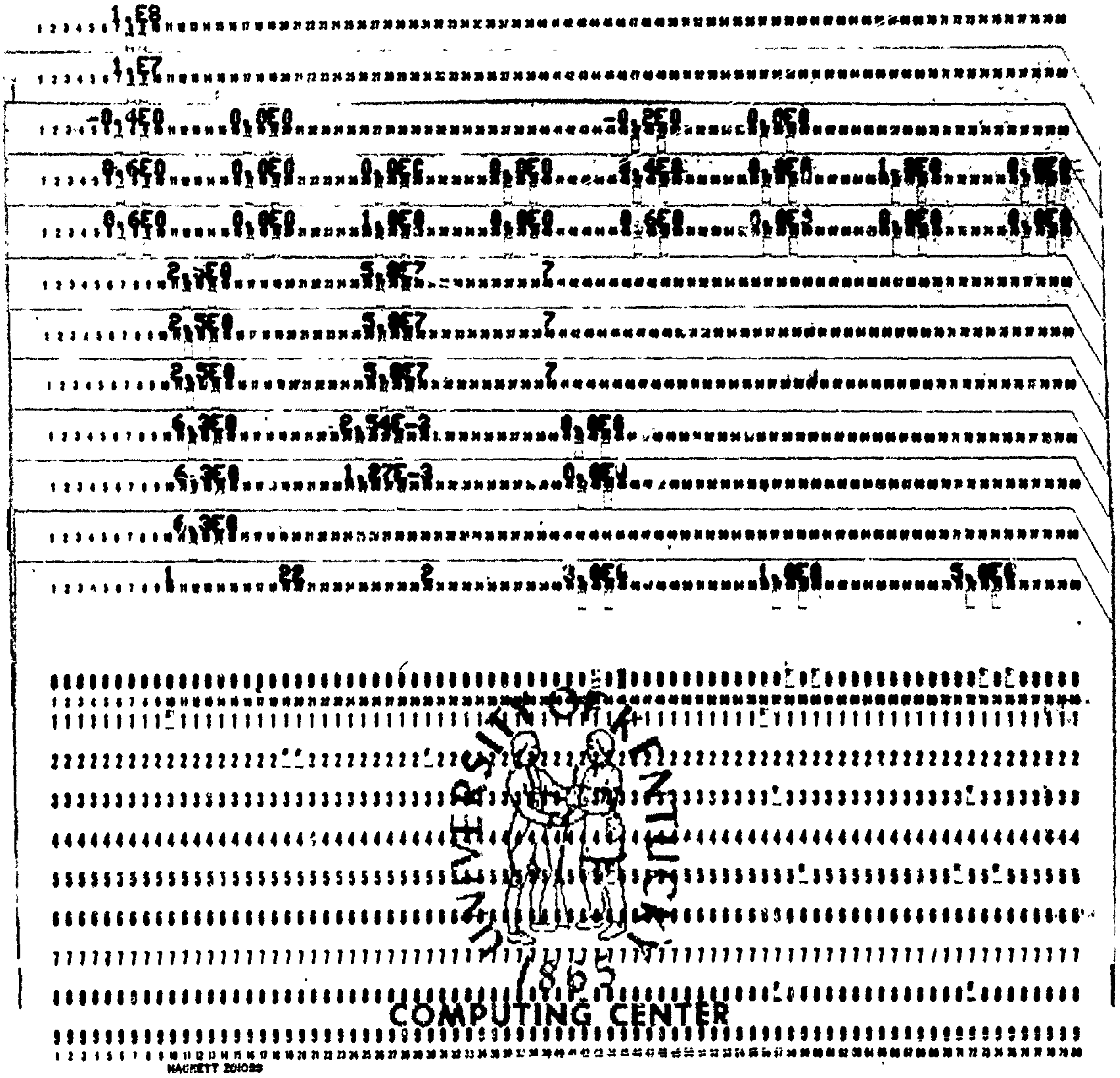


Figure 4-16. Input Cards, XTALK2, Example 4.

```
                                        XTALK2

                                   2 PARALLEL WIRES

                                  TYPE OF STRUCTURE= 1

                                LOAD STRUCTURE OPTION= 11

                           LINE LENGTH=  5.0000000D 00 METERS

                      DIELECTRIC CONSTANT OF THE MEDIUM=  3.0000 00

                      RELATIVE PERMEABILITY OF THE MEDIUM=  1.0000 00

REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A WIRE WITH RADIUS=  6.3000 00 MILS


WIRE NUMBER    WIRE RADIUS (MILS)           Z COORDINATE (METERS)              Y COORDINATE (METERS)

   1              6.3000 00                     1.2700-03                          0.0000-01
   2              6.3000 00                     2.5400-03                          0.0000-01

PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR=  0


REFERENCE WIRE ... STRANDED WITH EACH STRAND OF RADIUS=  2.5000 00 MILS
CONDUCTIVITY OF REFERENCE WIRE STRANDS=  5.8000 07 SIEMENS PER METER
NUMBER OF STRANDS=  7


WIRE NUMBER    WIRE STRAND RADIUS (MILS)              CONDUCTIVITY (SIEMENS PER METER)        NUMBER OF STRANDS

   1              2.5000 00                                 5.8000 07                              7

   2              2.5000 00                                 5.8000 07                              7

                  IMPEDANCE AT X=0          VOLTAGE SOURCE AT X=0          IMPEDANCE AT X=L          VOLTAGE SOURCE AT X=L
                       (OHMS)                      (VOLTS)                       (OHMS)                       (VOLTS)
ENTRY            REAL          IMAG           REAL          IMAG            REAL          IMAG           REAL          IMAG

 1  1         1.0000 00     0.0000-01      1.0000 00     0.0000-01       1.0000 03     0.0000-01      0.0000-01     0.0000-01
 2  2         1.0000 01     0.0000-01      0.0000-01     0.0000-01       1.0000 04     0.0000-01      1.0000 00     0.0000-01


  FREQUENCY(HERTZ)=  1.00000 07          SOLUTION ERROR=     0
 EIGEN SOLUTION ERROR=     0
 EIGEN SOLUTION PRECISION=  3.4360-02
 TRANSFORMATION MATRIX INVERSION ERROR=  0

                 WIRE        VOM(VOLTS)   VOA(DEGREES)          VLM(VOLTS)   VLA(DEGREES)

                  1          9.8310-01    1.7380 00             3.3380 00    -1.4700 02
                  2          1.8580-01    -6.2710 01            5.8760-01    -3.9380 01


  FREQUENCY(HERTZ)=  1.00000 06          SOLUTION ERROR=     0
 EIGEN SOLUTION ERROR=     0
 EIGEN SOLUTION PRECISION=  4.8160-03
 TRANSFORMATION MATRIX INVERSION ERROR=  0

                 WIRE        VOM(VOLTS)   VOA(DEGREES)          VLM(VOLTS)   VLA(DEGREES)

                  1          9.9760-01    4.4750-01             1.2470 00    8.1070 00
                  2          4.0500-02    -7.9900 01            2.8590-02    1.0550 02

 CORE USAGE       OBJECT CODE=   59696 BYTES,ARRAY AREA=     1312 BYTES,TOTAL AREA AVAILABLE=  161792  BYTES
 DIAGNOSTICS          NUMBER OF ERRORS=        0, NUMBER OF WARNINGS=        0, NUMBER OF EXTENSIONS=       15
 COMPILE TIME=     1.25 SEC,EXECUTION TIME=     0.12 SEC,     10.45.14     TUESDAY        4 OCT 77     WATFIV - JAN 1976 V1L5

         $STOP
```

Figure 4-17. Output Listing, XTALK2, Example 1.

```
                                        XTALK2

                                   2 PARALLEL WIRES

                                  TYPE OF STRUCTU-E= 1

                                LOAD STRUCTURE OPTION= 21

                             LINE LENGTH=  5.0000000 00 METERS

                          DIELECTRIC CONSTANT OF THE MEDIUM=  3.0000 00

                         RELATIVE PERMEABILITY OF THE MEDIUM=  1.0000 00

REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A WIRE WITH RADIUS=  6.3000 00 MILS

WIRE NUMBER    WIRE RADIUS (MILS)              Z COORDINATE (METERS)              Y COORDINATE (METERS)

  1            6.300D 00                       1.2700-03                          0.0000-01
  2            6.3000 00                       2.5400-03                          0.0000-01

PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR=  0

REFERENCE WIRE IS STRANDED WITH EA   STRAND OF RADIUS=  2.5000 00 MILS
CONDUCTIVITY OF REFERENCE WIRE STRANDS=  5.8000 07 SIEMENS PER METER
NUMBER OF STRANDS=  7

WIRE NUMBER    WIRE STRAND RADIUS (MILS)              CONDUCTIVITY (SIEMENS PER METER)      NUMBER OF STRANDS

  1            2.5000 00                              5.8000 07                             7

  2            2.5000 00                              5.8000 07                             7

               ADMITTANCE AT X=0        CURRENT SOURCE AT X=0       ADMITTANCE AT X=L        CURRENT SOURCE AT X=L
                  (SIEMENS)                    (AMPS)                   (SIEMENS)                  (AMPS)
ENTRY          REAL         IMAG         REAL         IMAG          REAL         IMAG         REAL         IMAG

 1   1      1.5000 00    0.0000-01    1.0000 00    0.0000-01    1.0000-03    0.0000-01    0.0000-01    0.0000-01
 2   2      1.0000-01    0.0000-01    0.0000-01    0.0000-01    1.0000-04    0.0000-01    1.0000-04    0.0000-01

 FREQUENCY(HERTZ)=  1.00000 07          SOLUTION ERROR=    0
EIGEN SOLUTION ERROR=    0
EIGEN SOLUTION PRECISION=  3.4350-02
TRANSFORMATION MATRIX INVERSION ERROR=  0

                 WIRE        VOM(VOLTS)   VOA(DEGREES)       VLM(VOLTS)   VLA(DEGREES)

                  1          9.8310-01    1.7380 00          3.3300 00    -1.4700 02
                  2          1.8580-01    -6.9710 01         5.8760-01    -3.9380 01

 FREQUENCY(HERTZ)=  1.00000 08          SOLUTION ERROR=    0
EIGEN SOLUTION ERROR=    0
EIGEN SOLUTION PRECISION=  4.8160-03
TRANSFORMATION MATRIX INVERSION ERROR=  0

                 WIRE        VOM(VOLTS)   VOA(DEGREES)       VLM(VOLTS)   VLA(DEGREES)

                  1          9.9760-01    4.4750-01          1.2470 00    8.1070 00
                  2          4.0500-02    -7.9900 01         2.8590-02    1.0550 02

CORE USAGE       OBJECT CODE=   59636 BYTES,ARRAY AREA=    1312 BYTES,TOTAL AREA AVAILABLE=  161792  BYTES
DIAGNOSTICS        NUMBER OF ERRORS=       0, NUMBER OF WARNINGS=       0, NUMBER OF EXTENSIONS=      26
COMPILE TIME=     1.29 SEC,EXECUTION TIME=     0.12 SEC,     10.45.56    TUESDAY        4 OCT 77    WATFIV - JAN 1976 V1L5

          $STOP
```

Figure 4-18. Output Listing, XTALK2, Example 2.

```
                                   XTALK2
                              2 PARALLEL WIRES
                             TYPE OF STRUCTURE= 1
                          LOAD STRUCTURE OPTION= 12
                      LINE LENGTH=  5.0000000D 00 METERS
                  DIELECTRIC CONSTANT OF THE MEDIUM=  3.0000 00
                 RELATIVE PERMEABILITY OF THE MEDIUM=  1.0000 00

REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A WIRE WITH RADIUS=  6.3000 00 MILS

WIRE NUMBER    WIRE RADIUS (MILS)            Z COORDINATE (METERS)                  Y COORDINATE (METERS)
  1                6.3000 00                      1.270D-03                              0.0000-01
  2                6.3000 00                      2.540D-03                              0.0000-01

PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR=  0

REFERENCE WIRE IS STRANDED WITH EACH STRAND OF RADIUS=  2.5000 00 MILS
CONDUCTIVITY OF REFERENCE WIRE STRANDS=  5.8000 07 SIEMENS PER METER
NUMBER OF STRANDS=  7

WIRE NUMBER    WIRE STRAND RADIUS (MILS)             CONDUCTIVITY (SIEMENS PER METER)        NUMBER OF STRANDS
  1                2.5000 00                                5.8000 07                              7

  2                2.5000 00                                5.8000 07                              7

                  IMPEDANCE AT X=0         VOLTAGE SOURCE AT X=0          IMPEDANCE AT X=L          VOLTAGE SOURCE AT X=L
                      (OHMS)                      (VOLTS)                      (OHMS)                      (VOLTS)
ENTRY           REAL         IMAG            REAL         IMAG            REAL         IMAG            REAL         IMAG
 1  1        3.0000 00    0.0000-01       3.0000 00    0.0000-01       2.0000 00    0.0000-01       1.0000 00    0.0000-01
 2  2        3.0000 00    0.0000-01       2.0000 00    0.0000-01       3.0000 00    0.0000-01       3.0000 00    0.0000-01
 1  2        2.0000 00    0.0000-01                                    1.0000 00    0.0000-01

 FREQUENCY(HERTZ)=  1.00000 07          SOLUTION ERROR=    0
EIGEN SOLUTION ERROR=     0
EIGEN SOLUTION PRECISION=  3.4350-02
TRANSFORMATION MATRIX INVERSION ERROR=  0
                 WIRE         VOM(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)
                  1           2.9990 00    -7.2040-01          1.0000 00    -2.8740 00
                  2           2.0000 00    -1.6160 00          2.9990 00    -6.8340-01

 FREQUENCY(HERTZ)=  1.00000 08          SOLUTION ERROR=    0
EIGEN SOLUTION ERROR=     0
EIGEN SOLUTION PRECISION=  4.8160-03
TRANSFORMATION MATRIX INVERSION ERROR=  0
                 WIRE         VOM(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)
                  1           2.9930 00    -8.7680-01          1.0070 00    3.2740 00
                  2           1.9990 00    5.2900-01           2.9960 00    -5.4630-01

CORE USAGE       OBJECT CODE=   59696 BYTES,ARRAY AREA=    1312 BYTES,TOTAL AREA AVAILABLE=  161792  BYTES
DIAGNOSTICS        NUMBER OF ERRORS=       0, NUMBER OF WARNINGS=       0, NUMBER OF EXTENSIONS=      26
COMPILE TIME=    1.27 SEC,EXECUTION TIME=     0.13 SEC,     10.46.26     TUESDAY        4 OCT 77    WATFIV - JAN 1976 V1L5
          $STOP
```

Figure 4-19. Output Listing, XTALK2, Example 3.

```
                                   XTALK2

                              2 PARALLEL WIRES

                             TYPE OF STRUCTURE= 1

                           LOAD STRUCTURE OPTION= 22

                      LINE LENGTH= 5.0000000D 00 METERS

               DIELECTRIC CONSTANT OF THE MEDIUM= 3.0000 00

               RELATIVE PERMEABILITY OF THE MEDIUM= 1.0000 00

 REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A WIRE WITH RADIUS= 6.3000 00 MILS

 WIRE NUMBER   WIRE RADIUS (MILS)          Z COORDINATE (METERS)          Y COORDINATE (METERS)

   1             6.3000 00                   1.2700-03                      0.0000-01
   2             6.3000 00                   2.5400-03                      0.0000-01

 PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR= 0

 REFERENCE WIRE IS STRANDED WITH EACH STRAND OF RADIUS= 2.5000 00 MILS
 CONDUCTIVITY OF REFERENCE WIRE STRANDS= 5.8000 07 SIEMENS PER METER
 NUMBER OF STRANDS= 7

 WIRE NUMBER   WIRE STRAND RADIUS (MILS)          CONDUCTIVITY (SIEMENS PER METER)      NUMBER OF STRANDS

   1              2.5000 00                              5.8000 07                           7
   2              2.5000 00                              5.8000 07                           7

              ADMITTANCE AT X=0        CURRENT SOURCE AT X=0      ADMITTANCE AT X=L        CURRENT SOURCE AT X=L
                 (SIEMENS)                   (AMPS)                  (SIEMENS)                  (AMPS)
 ENTRY        REAL          IMAG          REAL          IMAG          REAL          IMAG          REAL          IMAG

  1  1     6.0000-01     0.0000-01     1.0000 00     0.0000-01     6.0000-01     0.0000-01     0.0000-01     0.0000-01
  2  2     6.0000-01     0.0000-01     0.0000-01     0.0000-01     4.0000-01     0.0000-01     1.0000 00     0.0000-01
  1  2    -4.0000-01     0.0000-01                                -2.0000-01     0.0000-01

  FREQUENCY(HERTZ)=  1.00000 07          SOLUTION ERROR=    0
 EIGEN SOLUTION ERROR=    0
 EIGEN SOLUTION PRECISION=  3.4350-02
 TRANSFORMATION MATRIX INVERSION ERROR=  0

                 WIRE        VOM(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)

                  1          2.9990 00    -7.2040-01          1.0000 00    -2.5740 00
                  2          2.0000 00    -1.6160 00          2.9990 00    -6.5340-01

  FREQUENCY(HERTZ)=  1.00000 08          SOLUTION ERROR=    0
 EIGEN SOLUTION ERROR=    0
 EIGEN SOLUTION PRECISION=  4.8160-03
 TRANSFORMATION MATRIX INVERSION ERROR=  0

                 WIRE        VOM(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)

                  1          2.9930 00    -8.7580-01          1.0070 00    3.2740 00
                  2          1.9990 00    5.2920-01           2.9960 00    -5.4630-01

 CORE USAGE      OBJECT CODE=   59696 BYTES,ARRAY AREA=    1312 BYTES,TOTAL AREA AVAILABLE=  161792  BYTES
 DIAGNOSTICS       NUMBER OF ERRORS=       0, NUMBER OF WARNINGS=       0, NUMBER OF EXTENSIONS=      26
 COMPILE TIME=    1.29 SEC,EXECUTION TIME=     0.13 SEC,     10.47.52    TUESDAY       4 OCT 77    WATFIV - JAN 1976 V1L5

        $STOP
```

Figure 4-20. Output Listing, XTALK2, Example 4.

```
      1.E8
      1.E7
     1.0E1     0.0E0     0.0E0     0.0E0     1.0E4     0.0E0     1.0E0     0.0E0
     1.0E0     0.0E0     1.0E0     0.0E0     1.0E3     0.0E0     0.0E0     0.0E0
C    2    2   1.526657E-11
C    1    2  -5.128987E-12
C    1    1   1.526658E-11
C    2    2   2.654500E-11
C    1    2  -6.499984E-12
C    1    1   2.654488E-11
          2         11     5.0E0
```

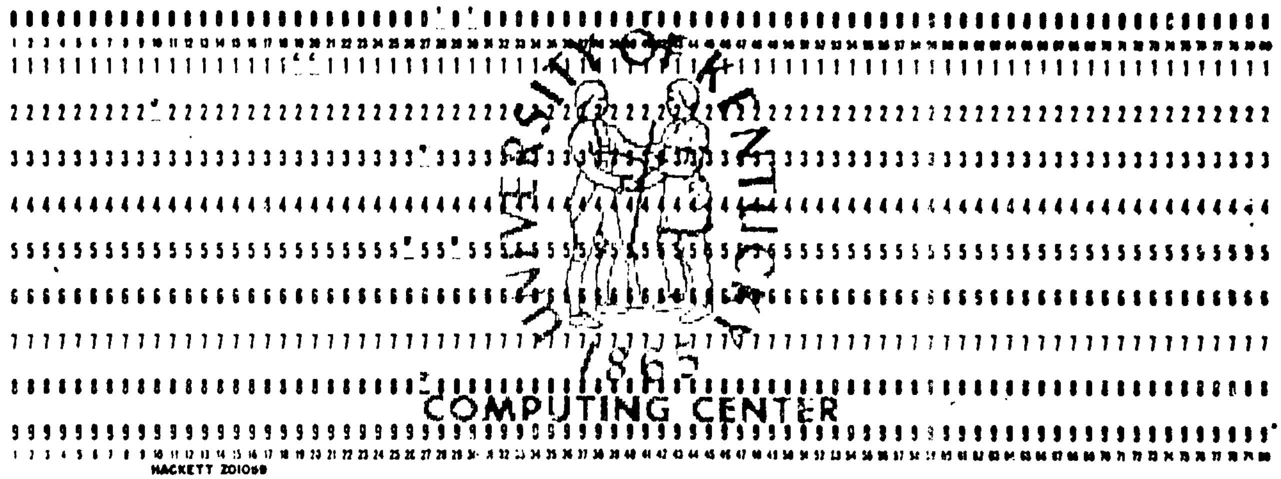


Figure 4-21. Input Cards, FLATPAK, Example 1.

```
      1,E8
      1,E7
    1,0E-1     0,0E0     0,0E0     0,0E0    1,0E-4     0,0E0    1,0E-4     0,0E0
    1,0E0     0,0E0     1,0E0     0,0E0    1,0E-3     0,0E0     0,0E0     0,0E0
C   2   2   1,5264975E-11
C   1   2  -5,128997E-12
C   1   1   1,5264975E-11
C   2   2   2,654590E-11
C   1   2  -6,499884E-12
C   1   1   2,654409E-11
         2         21     5,0E0
```

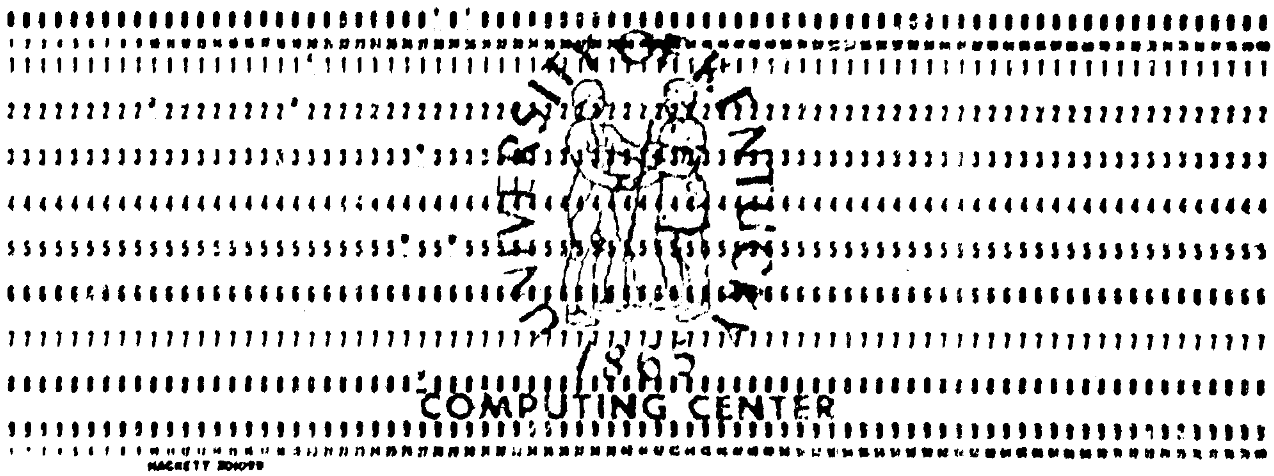


Figure 4-22. Input Cards, FLATPAK, Example 2.

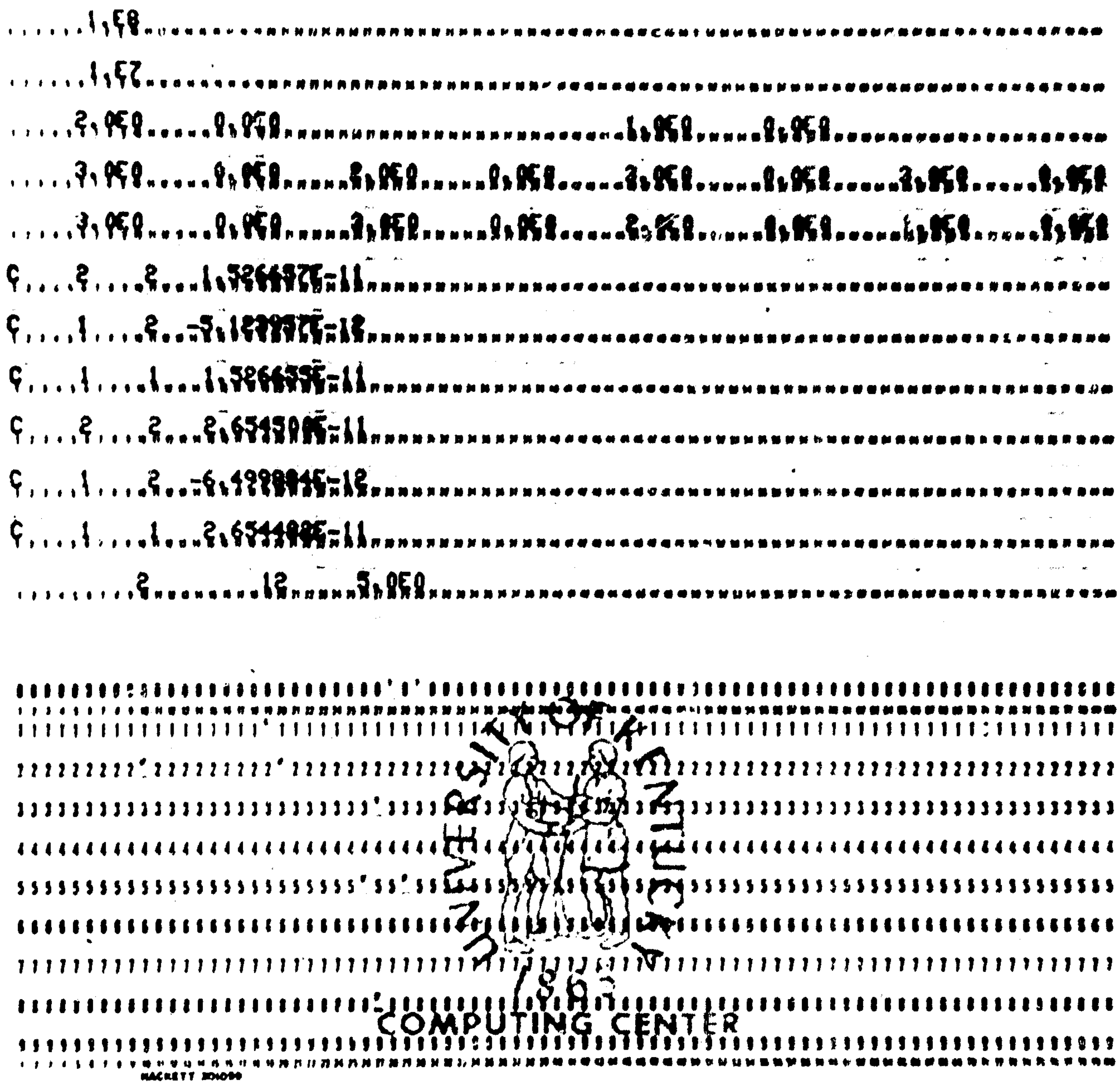


Figure 4-23. Input Cards FLATPAE, Example 5.

```
      1.50
      1.57
    -0.450    0.050                         -0.050    0.650
     0.650    0.050    0.050    0.050    0.450    0.050    1.050    0.050
     0.650    0.050    1.050    0.050    0.650    0.050    0.050    0.050
C    2    2    1.5264875E-11
C    1    2   -5.1279974E-12
C    1    1    1.5264858E-11
C    2    2    2.6548116E-11
C    1    2   -6.4990046E-12
C    1    1    2.6544066E-11
         2        22      5.050
```

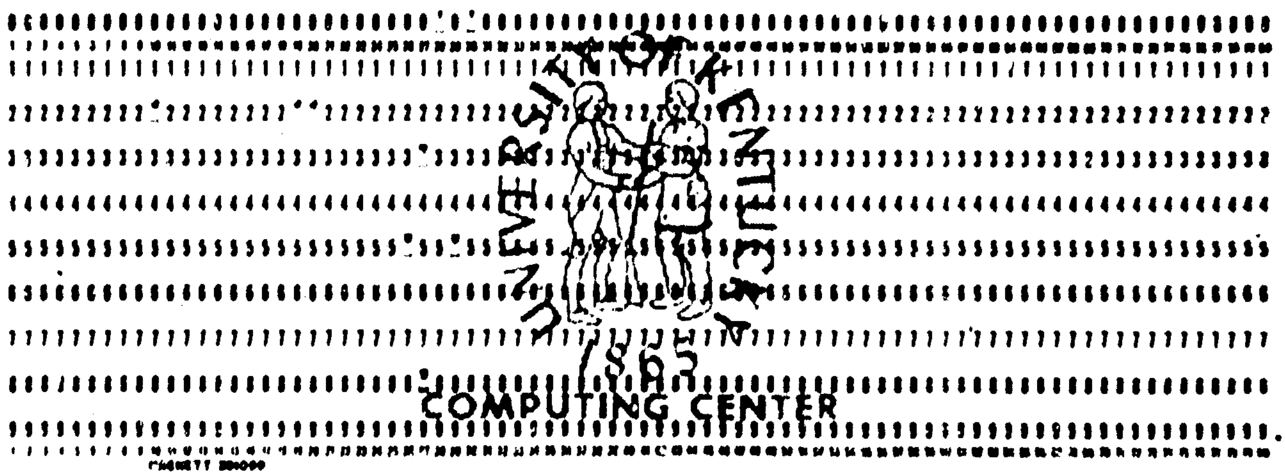


Figure 4-24. Input Cards, FLATPAK, Example 4.

```
                                        FLATPAK

                                   3 PARALLEL WIRES

                           LINE LENGTH=  5.0000000 00 METERS

                               LOAD STRUCTURE OPTION= 11


TRANSFORMATION MATRIX INVERSION ERROR=  9

              IMPEDANCE AT X=0        VOLTAGE SOURCE AT X=0        IMPEDANCE AT X=L        VOLTAGE SOURCE AT X=L
                   (OHMS)                   (VOLTS)                     (OHMS)                   (VOLTS)
ENTRY         REAL        IMAG         REAL        IMAG          REAL        IMAG          REAL        IMAG

  1  1     1.0000 00   0.0000-01    1.0000 00   0.0000-01     1.0000 03   0.0000-01     [illegible].0000-01  0.0000-01
  2  2     1.0000 01   0.0000-01    0.0000-01   0.0000-01     1.0000 04   0.0000-01     1.0000 00   0.0000-01


  FREQUENCY(HERTZ)=  1.00000 07          SOLUTION ERROR=     0
                 WIRE        VOM(VOLTS)   VOA(DEGREES)         VLM(VOLTS)   VLA(DEGREES)

                   1         9.8360-01    -8.0640-01           3.8970 00    -6.3760 01
                   2         7.2070-02     1.1960 02           1.5780 00    -1.0650 02


  FREQUENCY(HERTZ)=  1.00000 08          SOLUTION ERROR=     0
                 WIRE        VOM(VOLTS)   VOA(DEGREES)         VLM(VOLTS)   VLA(DEGREES)

                   1         9.9910-01    -4.0480-02           2.4850-01    -1.3210 02
                   2         6.6690-02     9.2290 01           1.6470 00    -1.7710 02

CORE USAGE      OBJECT CODE=    23992 BYTES,ARRAY AREA=      664 BYTES,TOTAL AREA AVAILABLE=  161.92  BYTES
DIAGNOSTICS       NUMBER OF ERRORS=       0, NUMBER OF WARNINGS=       0, NUMBER OF EXTENSIONS=       3
COMPILE TIME=     0.79 SEC,EXECUTION TIME=     0.06 SEC,     10.16.52    TUESDAY        4 OCT 77    WATFIV - JAN 1976 V1L[illegible]

        $STOP
```

Figure 4-25. Output Listing, FLATPAK, Example 1.

```
                                        FLATPAK

                                   2 PARALLEL WIRES

                         LINE LENGTH=  5.0000000D 00 METERS

                              LOAD STRUCTURE OPTION= 21


              ADMITTANCE AT X=0       CURRENT SOURCE AT X=0       ADMITTANCE AT X=L       CURRENT SOURCE AT X=L
                  (SIEMENS)                   (AMPS)                  (SIEMENS)                  (AMPS)
ENTRY          REAL         IMAG         REAL         IMAG         REAL         IMAG         REAL         IMAG

  1   1     1.0000 00    0.0000-01    1.0000 00    0.0000-01    1.0000-03    0.0000-01    0.0000-01    0.0000-01
  2   2     1.0000-01    0.0000-01    0.0000-01    0.0000-01    1.0000-04    0.0000-01    1.0000-04    0.0000-01
```

```
FREQUENCY(HERTZ)=  1.0000D 07          SOLUTION ERROR=    0
             WIRE        VOM(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)

              1          9.8360-01   -8.0640-01           3.8970 00   -8.3730 01
              2          7.2070-02    1.1960 02           1.8780 00   -1.0650 02
```

```
FREQUENCY(HERTZ)=  1.0000D 08          SOLUTION ERROR=    0
             WIRE        VOM(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)

              1          9.9910-01   -4.0680-02           2.4850-01   -1.3210 02
              2          6.6690-02    9.2290 01           1.5470 00   -1.7710 02

CORE USAGE       OBJECT CODE=   23002 BYTES,ARRAY AREA=     664 BYTES,TOTAL AREA AVAILABLE=  161792  BYTES
DIAGNOSTICS        NUMBER OF ERRORS=       0, NUMBER OF WARNINGS=       0, NUMBER OF EXTENSIONS=       3
COMPILE TIME=     1.07 SEC,EXECUTION TIME=     0.05 SEC,     10.24.20    TUESDAY        4 OCT 77    WATFIV - JAN 1976 V1L5

        $STOP
```

Figure 4-26. Output Listing, FLATPAK, Example 2.

```
                                        FLATPAK
                                   3 PARALLEL WIRES
                          LINE LENGTH=  5.0000000 00 METERS
                                LOAD STRUCTURE OPTION= 12

  TRANSFORMATION MATRIX INVERSION ERROR=  0

                  IMPEDANCE AT X=0          VOLTAGE SOURCE AT X=0          IMPEDANCE AT X=L           VOLTAGE SOURCE AT X=L
                      (OHMS)                        (VOLTS)                       (OHMS)                       (VOLTS)
  ENTRY            REAL         IMAG           REAL         IMAG           REAL         IMAG           REAL         IMAG

   1   1       3.0000D 00   0.0000D-01     3.0000D 00   0.0000D-01     2.0000D 00   0.0000D-01     1.0000D 00   0.0000D-01
   2   2       3.0000D 00   0.0000D-01     2.0000D 00   0.0000D-01     3.0000D 00   0.0000D-01     3.0000D 00   0.0000D-01
   1   2       2.0000D 00   0.0000D-01                                 1.0000D 00   0.0000D-01


  FREQUENCY(HERTZ)=  1.0000D 07          SOLUTION ERROR=     0
                  WIRE        VOM(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)

                    1         2.999D 00   -5.495D-01           1.0000 00   -2.036D 00
                    2         2.0000 00   -1.337D 00           2.999D 00   -5.317D-01


  FREQUENCY(HERTZ)=  1.0000D 08          SOLUTION ERROR=     0
                  WIRE        VOM(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)

                    1         2.998D 00   -1.387D 00           1.081D 00   -3.983D 00
                    2         2.0000 00   -2.945D 00           2.997D 00   -9.102D-01

  CORE USAGE        OBJECT CODE=   23992 BYTES,ARRAY AREA=     664 BYTES,TOTAL AREA AVAILABLE=  161792  BYTES
  DIAGNOSTICS         NUMBER OF ERRORS=       0, NUMBER OF WARNINGS=       0, NUMBER OF EXTENSIONS=       3
  COMPILE TIME=     0.52 SEC,EXECUTION TIME=     0.05 SEC,     10.26.52    TUESDAY        4 OCT 77    WATFIV - JAN 1976 V1L5

          $STOP
```

Figure 4-27. Output Listing, FLATPAK, Example 3.

```
                                        FLATPAK
                                    3 PARALLEL WIRES
                          LINE LENGTH=  5.000000D 00 METERS
                               LOAD STRUCTURE OPTION= 22

            ADMITTANCE AT X=0      CURRENT SOURCE AT X=0      ADMITTANCE AT X=L      CURRENT SOURCE AT X=L
               (SIEMENS)                  (AMPS)                  (SIEMENS)                 (AMPS)
ENTRY        REAL        IMAG          REAL        IMAG          REAL        IMAG          REAL        IMAG

 1   1    6.0000D-01  0.0000D-01    1.0000 00   0.0000D-01    6.0000D-01  0.0000D-01    0.0000D-01  0.0000D-01
 2   2    6.0000D-01  0.0000D-01    0.0000D-01  0.0000D-01    4.0000D-01  0.0000D-01    1.0000 00   0.0000D-01
 1   2   -4.0000D-01  0.0000D-01                             -2.0000D-01  0.0000D-01


FREQUENCY(HERTZ)=  1.00000 07          SOLUTION ERROR=    0
               WIRE         VOM(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)

                1           2.9990 00   -5.4950-01           1.0000 00   -2.0380 00
                2           2.0000 00   -1.3370 00           2.9990 00   -5.3170-01


FREQUENCY(HERTZ)=  1.00000 08          SOLUTION ERROR=    0
               WIRE         VOM(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)

                1           2.9980 00   -1.3870 00           1.0010 00   -3.9830 00
                2           2.0000 00   -2.9450 00           2.9970 00   -9.1020-01

CORE USAGE        OBJECT CODE=   23992 BYTES,ARRAY AREA=      664 BYTES,TOTAL AREA AVAILABLE=  131792  BYTES
DIAGNOSTICS          NUMBER OF ERRORS=       0, NUMBER OF WARNINGS=        0, NUMBER OF EXTENSIONS=       3
COMPILE TIME=      0.67 SEC,EXECUTION TIME=     0.03 SEC,     10.27.18    TUESDAY         4 OCT 77    WATFIV - JAN 1976 V1L5

       $STOP
```

Figure 4-28. Output Listing, FLATPAK, Example 4.

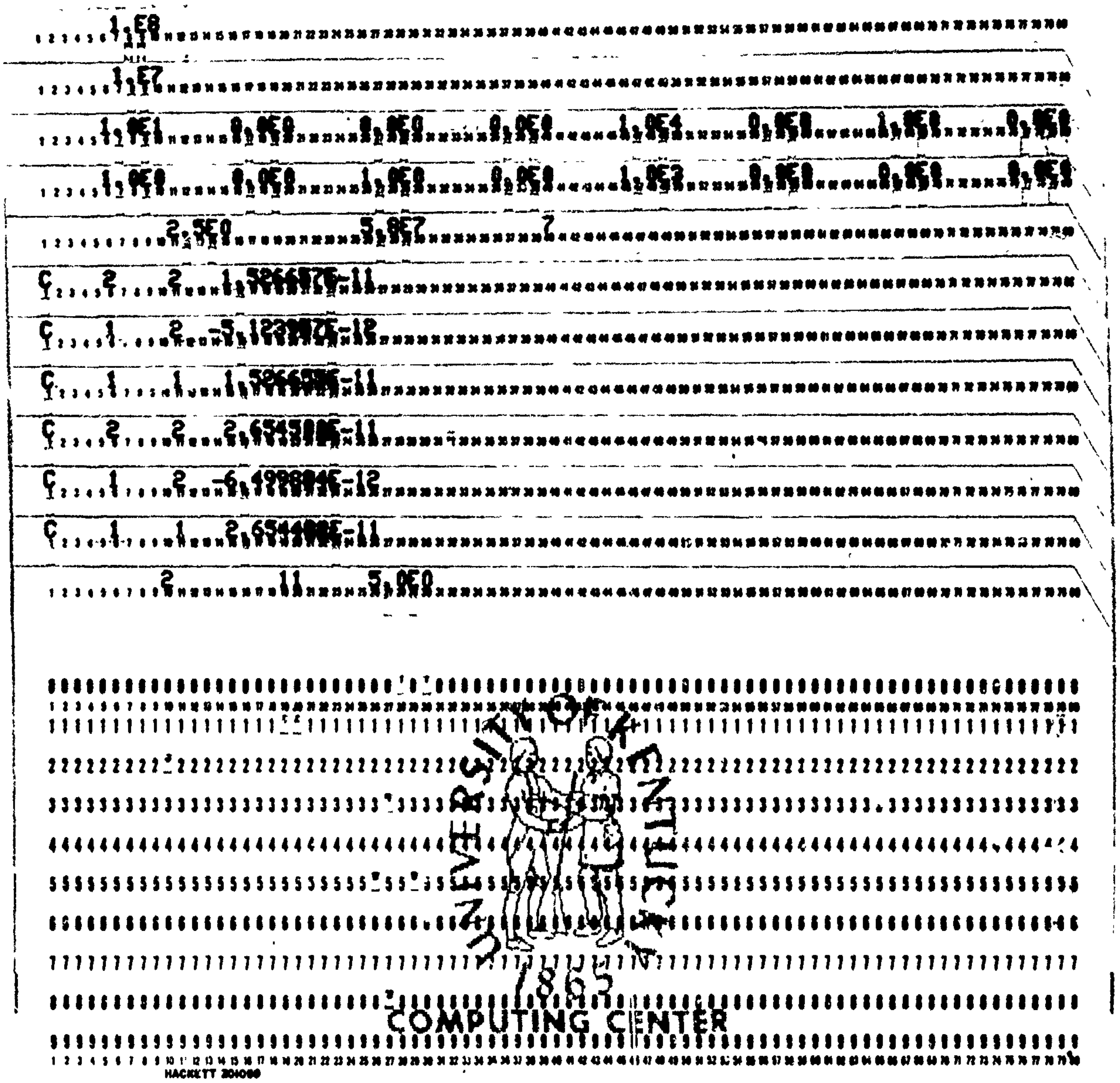


Figure 4-29. Input Cards, FLATPAK2, Example 1.

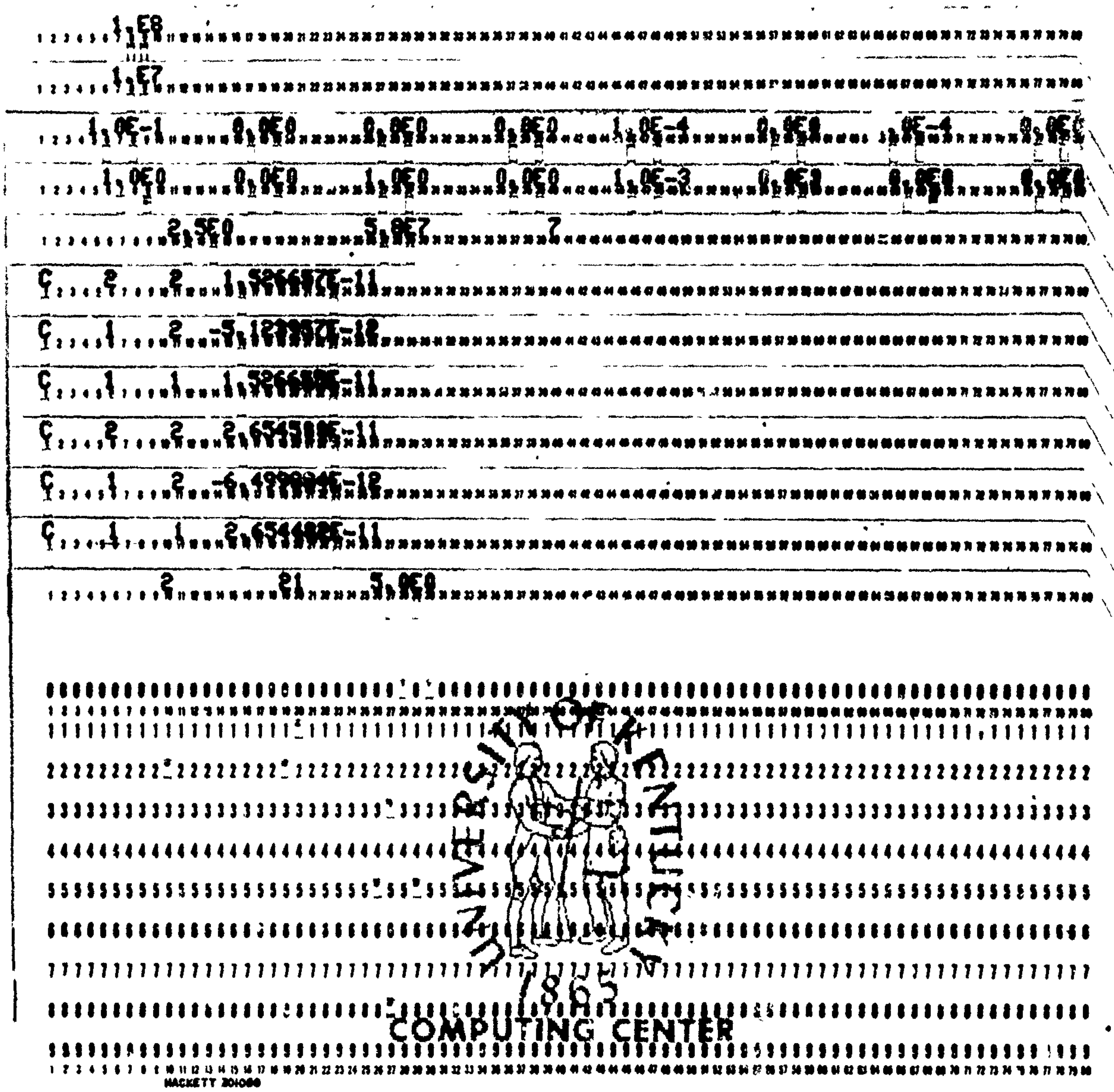


Figure 4-30. Input Cards, FLATPAK2, Example 2.

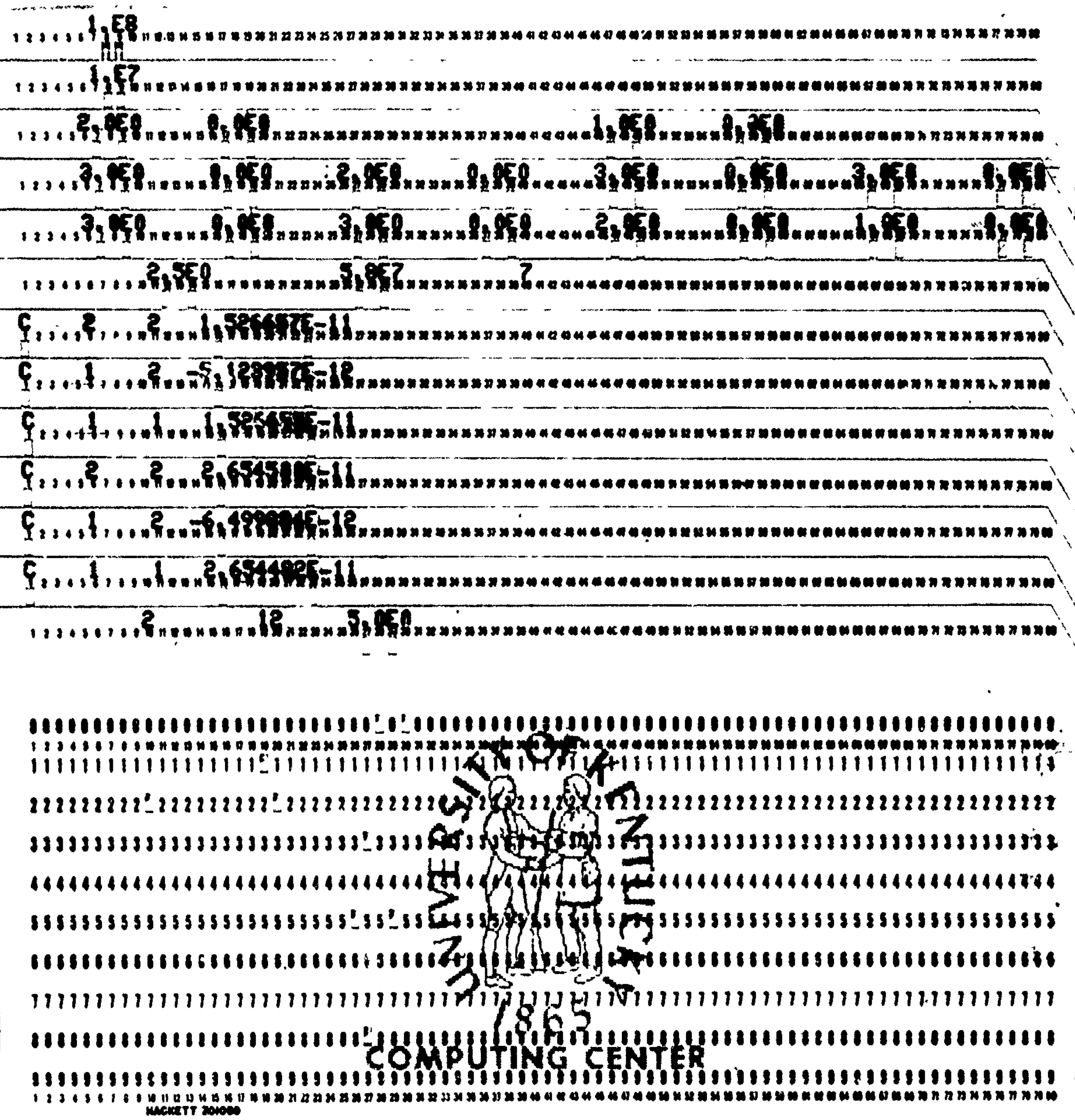


Figure 4-31. Input Cards, FLATPAK2, Example 3.

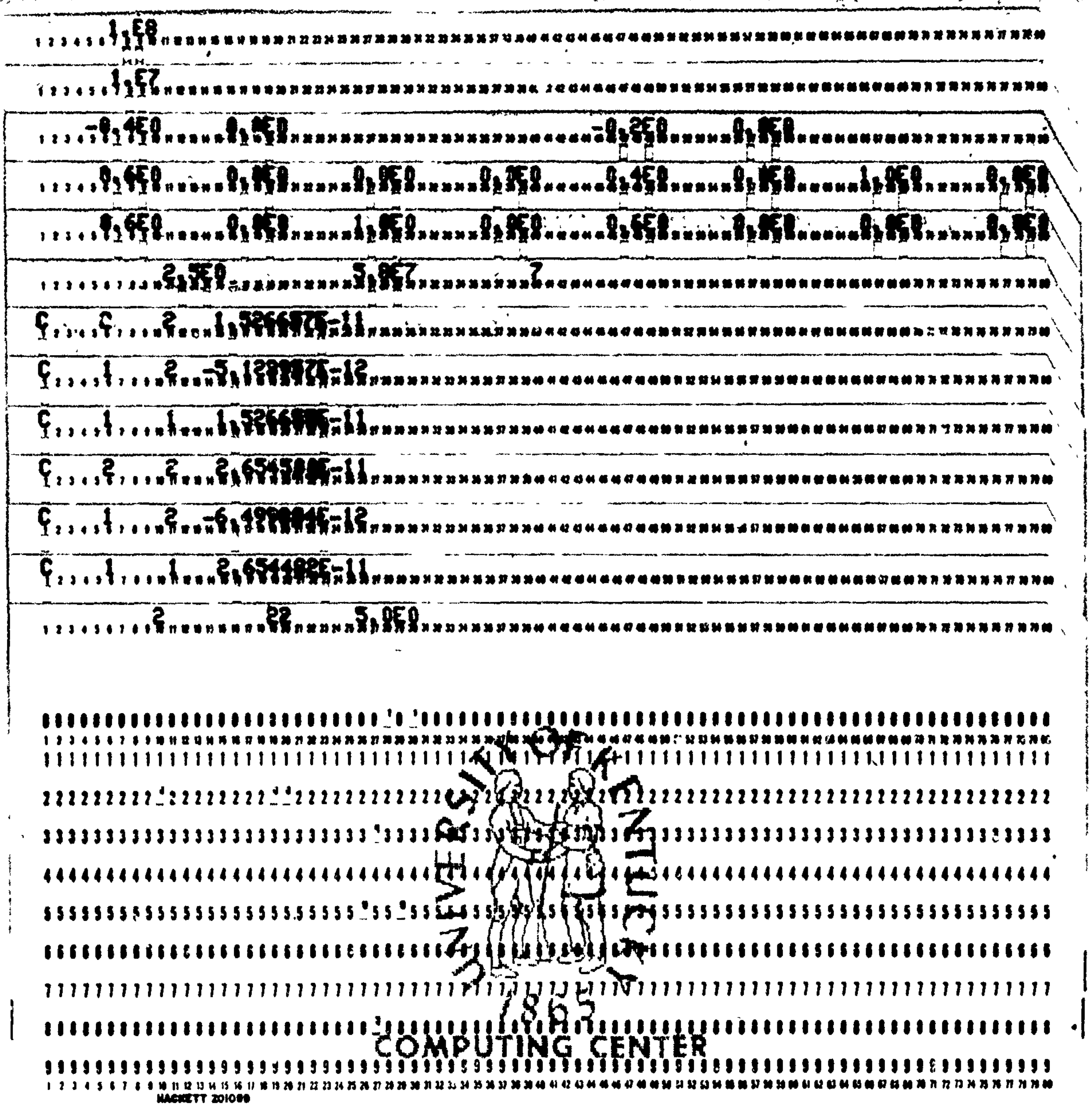


Figure 4-32. Input Cards, FLATPAK2, Example 4.

```
                                        FLATPAK2
                                   2 PARALLEL WIRES
                           LINE LENGTH=  3.0000000 00 METERS
                              LOAD STRUCTURE OPTION= 11

   PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR=  0

   PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR=  0

   WIRES ARE STRANDED WITH EACH STRAND OF RADIUS=  2.5000 00 MILS
   CONDUCTIVITY OF WIRE STRANDS=  5.8000 07 SIEMENS PER METER
   NUMBER OF STRANDS=  7

                 IMPEDANCE AT X=0         VOLTAGE SOURCE AT X=0        IMPEDANCE AT X=L          VOLTAGE SOURCE AT X=L
                     (OHMS)                      (VOLTS)                     (OHMS)                     (VOLTS)
   ENTRY          REAL         IMAG          REAL         IMAG          REAL         IMAG          REAL         IMAG
    1  1       1.0000 00    0.0000-01     1.0000 00    0.0000-01     1.0000 03    0.0000-01     0.0000-01    0.0000-01
    2  2       1.0000 01    0.0000-01     0.0000-01    0.0000-01     1.0000 04    0.0000-01     1.0000 00    0.0000-01

    FREQUENCY(HERTZ)=  1.00000 07          SOLUTION ERROR=    0
   EIGEN SOLUTION ERROR=    0
   EIGEN SOLUTION PRECISION=  1.2460-02
   TRANSFORMATION MATRIX INVERSION ERROR=  0
                 WIRE        VOM(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)
                  1          9.8370-01    -7.6170-01          3.7920 00    -8.6130 01
                  2          7.7690-02     1.1590 02          1.8130 00    -1.1330 02

    FREQUENCY(HERTZ)=  1.00000 08          SOLUTION ERROR=    0
   EIGEN SOLUTION ERROR=    0
   EIGEN SOLUTION PRECISION=  6.4190-03
   TRANSFORMATION MATRIX INVERSION ERROR=  0
                 WIRE        VOM(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)
                  1          9.9880-01    -6.0460-02          2.4210-01    -1.1730 02
                  2          4.9090-02     9.1940 01          1.9980 00    -1.7790 02

   CORE USAGE        OBJECT CODE=   53296 BYTES,ARRAY AREA=    1296 BYTES,TOTAL AREA AVAILABLE=  161792  BYTES
   DIAGNOSTICS          NUMBER OF ERRORS=        0, NUMBER OF WARNINGS=        0, NUMBER OF EXTENSIONS=      26
   COMPILE TIME=     1.23 SEC,EXECUTION TIME=     0.12 SEC,      10.31.12      TUESDAY        4 OCT 77    WATFIV - JAN 1976 V1L5

           $STOP
```

Figure 4-33. Output Listing, FLATPAK2, Example 1.

```
                                   FLATPAK2

                               3 PARALLEL WIRES

                     LINE LENGTH=  5.0000000 00 METERS

                           LOAD STRUCTURE OPTION= 21

PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR=  0

PER-UNIT-LENGTH CAPACITANCE MATRIX IN ERSION ERROR=  0

WIRES ARE STRANDED WITH EACH STRAND OF RADIUS=  2.5000 00 MILS
CONDUCTIVITY OF WIRE STRANDS=  5.8000 07 SIEMENS PER METER
NUMBER OF STRANDS=  7

              ADMITTANCE AT X=0         CURRENT SOURCE AT X=0         ADMITTANCE AT X=L         CURRENT SOURCE AT X=L
                  (SIEMENS)                    (AMPS)                     (SIEMENS)                     (AMPS)
ENTRY          REAL         IMAG          REAL         IMAG          REAL         IMAG          REAL         IMAG

 1   1      1.0000D 00   0.0000D-01    1.0000D 00   0.0000D-01    1.0000D-03   0.0000D-01    0.0000D-01   0.0000D-01
 2   2      1.0000D-01   0.0000D-01    0.0000D-01   0.0000D-01    1.0000D-04   0.0000D-01    1.0000D-04   0.0000D-01


  FREQUENCY(HERTZ)=  1.00000 07          SOLUTION ERROR=    0
 EIGEN SOLUTION ERROR=     0
 EIGEN SOLUTION PRECISION=  1.2460-02
 TRANSFORMATION MATRIX INVERSION ERROR=  0

                 WIRE        VOM(VOLTS)    VOA(DEGREES)        VLM(VOLTS)    VLA(DEGREES)

                  1          9.8370-01    -7.6170-01           3.7920 00    -8.6180 01
                  2          7.7690-02     1.1560 02           1.6130 00    -1.1330 02


  FREQUENCY(HERTZ)=  1.00000 08          SOLUTION ERROR=    0
 EIGEN SOLUTION ERROR=     0
 EIGEN SOLUTION PRECISION=  5.4180-03
 TRANSFORMATION MATRIX INVERSION ERROR=  0

                 WIRE        VOM(VOLTS)    VOA(DEGREES)        VLM(VOLTS)    VLA(DEGREES)

                  1          9.9880-01    -6.0460-02           2.4210-01    -1.1730 02
                  2          6.5090-02     9.1640 01           1.5080 00    -1.7700 02

 CORE USAGE       OBJECT CODE=   53296 BYTES,ARRAY AREA=    1296 BYTES,TOTAL AREA AVAILABLE=  161792  BYTES
 DIAGNOSTICS        NUMBER OF ERRORS=       0, NUMBER OF WARNINGS=       0, NUMBER OF EXTENSIONS=      26
 COMPILE TIME=    1.32 SEC,EXECUTION TIME=     0.11 SEC,     10.33.38    TUESDAY        4 OCT 77    WATFIV - JAN 1976 V1L5

         $STOP
```

Figure 4-34. Output Listing, FLATPAK2, Example 2.

FLATPAK2

3 PARALLEL WIRES

LINE LENGTH= 5.0000000D 00 METERS

LOAD STRUCTURE OPTION= 12

PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR= 0

PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR= 0

WIRES ARE STRANDED WITH EACH STRAND OF RADIUS= 2.5000 00 MILS
CONDUCTIVITY OF WIRE STRANDS= 5.8000 07 SIEMENS PER METER
NUMBER OF STRANDS= 7

		IMPEDANCE AT X=0 (OHMS)		VOLTAGE SOURCE AT X=0 (VOLTS)		IMPEDANCE AT X=L (OHMS)		VOLTAGE SOURCE AT X=L (VOLTS)	
ENTRY		REAL	IMAG	REAL	IMAG	REAL	IMAG	REAL	IMAG
1	1	3.0000 00	0.0000D-01	3.0000 00	0.0000-01	2.0000 00	0.0000D-01	1.0000 00	0.0000D-01
2	2	3.0000 00	0.0000-01	2.0000 00	0.0000-01	3.0000 00	0.0000-01	3.0000 00	0.0000-01
1	2	2.0000 00	0.0000-01			1.0000 00	0.0000D-01		

FREQUENCY(HERTZ)= 1.0000D 07 SOLUTION ERROR= 0
EIGEN SOLUTION ERROR= 0
EIGEN SOLUTION PRECISION= 1.2480-02
TRANSFORMATION MATRIX INVERSION ERROR= 0

WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	2.9990 00	-5.5520-01	1.0000 00	-2.0350 00
2	2.0000 00	-1.3410 00	2.9990 00	-5.3530-01

FREQUENCY(HERTZ)= 1.0000D 08 SOLUTION ERROR= 0
EIGEN SOLUTION ERROR= 0
EIGEN SOLUTION PRECISION= 5.4180-03
TRANSFORMATION MATRIX INVERSION ERROR= 0

WIRE	VOM(VOLTS)	VOA(DEGREES)	VLM(VOLTS)	VLA(DEGREES)
1	2.9940 00	-1.4520 00	9.9930-01	-4.0590 00
2	1.9970 00	-3.0230 00	2.9940 00	-9.6950-01

CORE USAGE OBJECT CODE= 53296 BYTES,ARRAY AREA= 1296 BYTES,TOTAL AREA AVAILABLE= 161792 BYTES
DIAGNOSTICS NUMBER OF ERRORS= 0, NUMBER OF WARNINGS= 0, NUMBER OF EXTENSIONS= 26
COMPILE TIME= 1.15 SEC,EXECUTION TIME= 0.10 SEC, 10.38.35 TUESDAY 4 OCT 77 WATFIV - JAN 1976 V1L5

$STOP

Figure 4-35. Output Listing, FLATPAK2, Example 3.

```
                                   FLATPAK2

                               3 PARALLEL WIRES

                       LINE LENGTH=  5.0000000D 00 METERS

                           LOAD STRUCTURE OPTION= 22


    PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR=  0

    PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR=  0


    WIRES ARE STRANDED WITH EACH STRAND OF RADIUS=  2.8000 00 MILS
    CONDUCTIVITY OF WIRE STRANDS=  5.8000 07 SIEMENS PER METER
    NUMBER OF STRANDS=  7


                  ADMITTANCE AT X=0        CURRENT SOURCE AT X=0        ADMITTANCE AT X=L       CURRENT SOURCE AT X=L
                     (SIEMENS)                    (AMPS)                    (SIEMENS)                  (AMPS)
    ENTRY          REAL          IMAG         REAL          IMAG          REAL          IMAG         REAL          IMAG

    1   1      6.0000-01    0.0000-01    1.0000 00    0.0000-01    6.0000-01    0.0000-01    0.0000-01    0.0000-01
    2   2      6.0000-01    0.0000-01    0.0000-01    0.0000-01    4.0000-01    0.0000-01    1.0000 00    0.0000-01
    1   2     -4.0000-01    0.0000-01                              -2.0000-01    0.0000-01


    FREQUENCY(HERTZ)=  1.00000 07           SOLUTION ERROR=     0
    EIGEN SOLUTION ERROR=     0
    EIGEN SOLUTION PRECISION=  1.2460-07
    TRANSFORMATION MATRIX INVERSION ERROR=  0

                  WIRE        VOM(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)

                   1          2.9990 00   -5.5520-01           1.0000 00   -2.0350 00
                   2          2.0000 00   -1.3410 00           2.9990 00   -5.3530-01


    FREQUENCY(HERTZ)=  1.00000 08           SOLUTION ERROR=     0
    EIGEN SOLUTION ERROR=     0
    EIGEN SOLUTION PRECISION=  5.4180-03
    TRANSFORMATION MATRIX INVERSION ERROR=  0

                  WIRE        VOM(VOLTS)   VOA(DEGREES)        VLM(VOLTS)   VLA(DEGREES)

                   1          2.9940 00   -1.4520 00           9.9930-01   -4.0590 00
                   2          1.9970 00   -3.0230 00           2.9940 00   -9.6950-01

    CORE USAGE       OBJECT CODE=   53296 BYTES,ARRAY AREA=    1296 BYTES,TOT'L AREA AVAILABLE=  161792  BYTES
    DIAGNOSTICS        NUMBER OF ERRORS=       0, NUMBER OF WARNINGS=       0, NUMBER OF EXTENSIONS=     26
    COMPILE TIME=     0.97 SEC,EXECUTION TIME=     0.10 SEC,     10.39.29    TUESDAY        4 OCT 77    WATFIV - JAN 1976 V1L5

           $STOP
```

Figure 4-36. Output Listing, FLATPAK2, Example 4.

V. SUMMARY

Four digital computer programs, XTALK, XTALK 2, FLATPAK, FLATPAK 2, for determining the electromagnetic coupling within an (n+1) conductor, uniform transmission line are presented. Sinusoidal steady state behavior of the line as well as the TEM or "quasi-TEM" mode of propagation are assumed.

XTALK and XTALK 2 consider lines consisting of n wires (cylindrical conductors) and a reference conductor. The surrounding medium is homogeneous and lossless. XTALK assumes that all (n+1) conductors are perfect conductors whereas XTALK 2 considers the conductors to be lossy. There are three choices for the reference conductor: a wire, a ground plane, an overall cylindrical shield.

FLATPAK and FLATPAK 2 consider (n+1) wire ribbon (flatpack) cables in which all wires are identical and are coated with cylindrical, dielectric insulations of identical thicknesses. All wires lie in a horizontal plane and all adjacent wires are separated by identical distances. FLATPAK considers the wires to be perfect conductors and FLATPAK 2 considers the wires to be lossy. The dielectric insulations are considered to be lossless.

General termination networks are provided for at the ends of the line and the programs compute the voltages (with respect to the reference conductor) at the terminals of these termination networks for sinusoidal steady state excitation of the line.

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APPENDICES

APPENDIX A

XTALK

Program Listing

```
C************************************************************************
C
C           PROGRAM XTALK
C           (FORTRAN IV, DOUBLE PRECISION)
C           WRITTEN BY
C                CLAYTON R. PAUL
C                DEPARTMENT OF ELECTRICAL ENGINEERING
C                UNIVERSITY OF KENTUCKY
C                LEXINGTON, KENTUCKY 40506
C
C     A DIGITAL COMPUTER PROGRAM TO COMPUTE THE TERMINAL VOLTAGES
C     (WITH RESPECT TO THE REFERENCE CONDUCTOR) AT THE ENDS OF A
C     MULTICONDUCTOR TRANSMISSION LINE FOR THE TEM MODE OF
C     PROPAGATION.
C
C     THE DISTRIBUTED PARAMETER, MULTICONDUCTOR TRANSMISSION LINE
C     EQUATIONS ARE SOLVED FOR STEADY STATE, SINUSOIDAL EXCITATION
C     OF THE LINE.
C
C     THE LINE CONSISTS OF N WIRES (CYLINDRICAL CONDUCTORS) AND A
C     REFERENCE CONDUCTOR. THE REFERENCE CONDUCTOR MAY BE A WIRE
C     (TYPE=1), AN INFINITE GROUND PLANE (TYPE=2), OR AN OVERALL
C     CYLINDRICAL SHIELD (TYPE=3)
C
C     THE N WIRES ARE ASSUMED TO BE PARALLEL TO EACH OTHER AND THE
C     REFERENCE CONDUCTOR.
C
C     THE N WIRES AND THE REFERENCE CONDUCTOR ARE ASSUMED TO BE
C     PERFECT CONDUCTORS.
C
C     THE LINE IS IMMERSED IN A LINEAR, ISOTROPIC, AND HOMOGENEOUS
C     MEDIUM WITH A RELATIVE PERMEABILITY OF MUR AND A RELATIVE
C     DIELECTRIC CONSTANT OF ER. THE MEDIUM IS ASSUMED TO BE LOSSLESS.
C
C     LOAD STRUCTURE OPTION DEFINITIONS:
C        OPTION=11,THEVENIN EQUIVALENT LOAD STRUCTURES WITH DIAGONAL
C                  IMPEDANCE MATRICES
C        OPTION=12,THEVENIN EQUIVALENT LOAD STRUCTURES WITH FULL
C                  IMPEDANCE MATRICES
C        OPTION=21,NORTON EQUIVALENT LOAD STRUCTURES WITH DIAGONAL
C                  ADMITTANCE MATRICES
C        OPTION=22,NORTON EQUIVALENT LOAD STRUCTURES WITH FULL
C                  ADMITTANCE MATRICES
C
C     SUBROUTINES USED: LEQT1C
C
C************************************************************************
C
C     ALL VECTORS AND MATRICES IN THE FOLLOWING DIMENSION STATEMENTS
C     SHOULD BE OF SIZE N WHERE N IS THE NUMBER OF WIRES(EXCLUSIVE OF
C     THE REFERENCE CONDUCTOR), I.E., IO(N),IL(N),YO(N,N),YL(N,N),B(N),
C     A(N,N),WA(N),M1(N,N),M2(N,N),V1(N),V2(N)
C
      IMPLICIT REAL*8 (A-H,O-Z)
      INTEGER TYPE,OPTION
      REAL*8 L,MUO2PI,MUR
      COMPLEX*16 XJ,IO( 2),IL( 2),YO( 2, 2),YL( 2, 2),A( 2, 2),B( 2),
     1WA( 2),M1( 2, 2),M2( 2, 2),V1( 2),V2( 2),SUMO,SUML,VO,VL,ZEROC,
     2C,A1,A2,ONEC
      DATA PI/3.141592653D0/,V/2.997925D8/
      DATA CMTM/2.54D-5/,MUO2PI/2.D-7/,P5/.5D0/,ZERO/0.D0/,ONE/1.D0/,
```

```
     1TWO/2.D0/,FOUR/4.D0/,ONE80/180.D0/                                XTALK062
      ONEC=DCMPLX(1.D0,0.D0)                                            XTALK063
      ZEROC=DCMPLX(0.D0,0.D0)                                           XTALK064
      XJ=DCMPLX(0.D0,1.D0)                                              XTALK065
C                                                                       XTALK066
C*****FREQUENCY INDEPENDENT CALCULATIONS*********************************XTALK067
C                                                                       XTALK068
C     READ AND PRINT INPUT DATA                                         XTALK069
C                                                                       XTALK070
      READ(5,1) TYPE,OPTION,N,ER,MUR,L                                  XTALK071
    1 FORMAT(9X,I1,2(8X,I2),3(5X,E10.3))                                XTALK072
      IF(TYPE.GE.1.AND.TYPE.LE.3) GO TO 3                               XTALK073
      WRITE(6,2)                                                        XTALK074
    2 FORMAT(' STRUCTURE TYPE ERROR'//' TYPE MUST EQUAL 1,2,OR 3'///)   XTALK075
      GO TO 82                                                          XTALK076
    3 IF(OPTION.EQ.11.OR.OPTION.EQ.12) GO TO 5                          XTALK077
      IF(OPTION.EQ.21.OR.OPTION.EQ.22) GO TO 5                          XTALK078
      WRITE(6,4)                                                        XTALK079
    4 FORMAT(' LOAD STRUCTURE OPTION ERROR'//' OPTION MUST EQUAL 11,12,2XTALK080
     11,OR 22'///)                                                      XTALK081
      GO TO 82                                                          XTALK082
    5 WRITE(6,6) N,TYPE,OPTION,L,ER,MUR                                 XTALK083
    6 FORMAT(1H1,50X,'XTALK'///                                         XTALK084
     145X,I2,' PARALLEL WIRES'///                                       XTALK085
     243X,' TYPE OF STRUCTURE= ',I1///                                  XTALK086
     341X,' LOAD STRUCTURE OPTION= ',I2///                              XTALK087
     439X,' LINE LENGTH= ',1PE13.6,' METERS'///                         XTALK088
     532X,' DIELECTRIC CONSTANT OF THE MEDIUM= ',1PE10.3///             XTALK089
     631X,' RELATIVE PERMEABILITY OF THE MEDIUM= ',1PE10.3///)          XTALK090
      GO TO (7,15,11),TYPE                                              XTALK091
    7 READ(5,8) RWO                                                     XTALK092
    8 FORMAT(5X,E10.3)                                                  XTALK093
      WRITE(6,9) RWO                                                    XTALK094
    9 FORMAT(' REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A WIRE WITH RADIXTALK095
     1US= ',1PE10.3,' MILS'////)                                        XTALK096
      RWO=RWO*CMTM                                                      XTALK097
      WRITE(6,10)                                                       XTALK098
   10 FORMAT(' WIRE NUMBER',4X,'WIRE RADIUS (MILS)',18X,                XTALK099
     1'Z COORDINATE (METERS)',24X,'Y COORDINATE (METERS)',//)           XTALK100
      GO TO 19                                                          XTALK101
   11 READ(5,12) RS                                                     XTALK102
   12 FORMAT(5X,E10.3)                                                  XTALK103
      WRITE(6,13) RS                                                    XTALK104
   13 FORMAT(' REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A CYLINDRICAL OVXTALK105
     1ERALL SHIELD WITH INTERIOR RADIUS= ',1PE10.3,' METERS'////)       XTALK106
      RS2=RS*RS                                                         XTALK107
      WRITE(6,14)                                                       XTALK108
   14 FORMAT(' WIRE NUMBER',2X,'WIRE RADIUS (MILS)', 2X,'SEPARATION BETWXTALK109
     1EEN WIRE AND CENTER OF SHIELD (METERS)',6X,'ANGULAR COORDINATE (DEXTALK110
     2GREES)'//)                                                        XTALK111
      GO TO 18                                                          XTALK112
   15 WRITE(6,16)                                                       XTALK113
   16 FORMAT(' REFERENCE CONDUCTOR FOR LINE VOLTAGES IS AN INFINITE GROUXTALK114
     1ND PLANE'////)                                                    XTALK115
      WRITE(6,17)                                                       XTALK116
   17 FORMAT(' WIRE NUMBER',4X,'WIRE RADIUS (MILS)',18X,                XTALK117
     1'HORIZONTAL COORDINATE (METERS)',16X,'WIRE HEIGHT (METERS)',//)   XTALK118
C                                                                       XTALK119
C     READ AND PRINT LINE DIMENSIONS AND COMPUTE THE CHARACTERISTIC     XTALK120
C     IMPEDANCE MATRIX, ZC (STORE ZC IN ARRAY M1)                       XTALK121
C                                                                       XTALK122
```

```
   18 C=MUO2PI*ONEC*V*DSQRT(MUR/ER)                                        XTALK123
      DO 24 I=1,N                                                          XTALK124
      READ(5,19) RW,Z,Y                                                    XTALK125
   19 FORMAT(3(5X,E10.3))                                                  XTALK126
      WRITE(6,20) I,RW,Z,Y                                                 XTALK127
   20 FORMAT(2X,I2,13X,1PE10.3,27X,1PE10.3,35X,1PE10.3/)                   XTALK128
      V1(I)=ONEC*Z                                                         XTALK129
      V2(I)=ONEC*Y                                                         XTALK130
      RW=RW*CMTM                                                           XTALK131
      GO TO (21,22,23),TYPE                                                XTALK132
   21 DI2=Z*Z+Y*Y                                                          XTALK133
      M1(I,I)=C*DLOG(DI2/(RW*RW0))                                         XTALK134
      GO TO 24                                                             XTALK135
   22 M1(I,I)=C*DLOG(TWO*Y/RW)                                             XTALK136
      GO TO 24                                                             XTALK137
   23 M1(I,I)=C*DLOG((RS2-Z*Z)/(RS*RW))                                    XTALK138
   24 CONTINUE                                                             XTALK139
      IF(N.EQ.1) GO TO 29                                                  XTALK140
      K1=N-1                                                               XTALK141
      DO 28 I=1,K1                                                         XTALK142
      K2=I+1                                                               XTALK143
      DO 28 J=K2,N                                                         XTALK144
      ZI=DREAL(V1(I))                                                      XTALK145
      ZJ=DREAL(V1(J))                                                      XTALK146
      YI=DREAL(V2(I))                                                      XTALK147
      YJ=DREAL(V2(J))                                                      XTALK148
      GO TO (25,26,27),TYPE                                                XTALK149
   25 DI2=ZI*ZI+YI*YI                                                      XTALK150
      DJ2=ZJ*ZJ+YJ*YJ                                                      XTALK151
      ZD=ZI-ZJ                                                             XTALK152
      YD=YI-YJ                                                             XTALK153
      DIJ2=ZD*ZD+YD*YD                                                     XTALK154
      M1(I,J)=P5*C*DLOG(DI2*DJ2/(RW0*RW0*DIJ2))                            XTALK155
      M1(J,I)=M1(I,J)                                                      XTALK156
      GO TO 28                                                             XTALK157
   26 ZD=ZI-ZJ                                                             XTALK158
      YD=YI-YJ                                                             XTALK159
      DIJ2=ZD*ZD+YD*YD                                                     XTALK160
      M1(I,J)=P5*C*DLOG(ONE+FOUR*YI*YJ/DIJ2)                               XTALK161
      M1(J,I)=M1(I,J)                                                      XTALK162
      GO TO 28                                                             XTALK163
   27 THETA=(YI-YJ)*PI/ONE80                                               XTALK164
      RI2=ZI*ZI                                                            XTALK165
      RJ2=ZJ*ZJ                                                            XTALK166
      M1(I,J)=P5*C*DLOG((RJ2/RS2)*(RI2*RJ2+RS2*RS2-TWO*ZI*ZJ*RS2*          XTALK167
     1DCOS(THETA))/(RI2*RJ2+RJ2*RJ2-TWO*ZI*ZJ*RJ2*DCOS(THETA)))            XTALK168
      M1(J,I)=M1(I,J)                                                      XTALK169
   28 CONTINUE                                                             XTALK170
C                                                                          XTALK171
C     COMPUTE THE INVERSE OF THE CHARACTERISTIC IMPEDANCE MATRIX, ZCINV    XTALK172
C     (STORE ZCINV IN ARRAY M2)                                            XTALK173
C                                                                          XTALK174
   29 DO 31 I=1,N                                                          XTALK175
      DO 30 J=1,N                                                          XTALK176
      A(I,J)=M1(I,J)                                                       XTALK177
   30 M2(I,J)=ZEROC                                                        XTALK178
   31 M2(I,I)=ONEC                                                         XTALK179
      CALL LEQT1C(A,N,N,M2,N,N,0,WA,KER)                                   XTALK180
      KER=KER-128                                                          XTALK181
C                                                                          XTALK182
C     READ AND PRINT ENTRIES IN LOAD ADMITTANCE(IMPEDANCE) MATRICES        XTALK183
```

```
C     AND SHORT CIRCUIT CURRENT SOURCE(OPEN CIRCUIT VOLTAGE SOURCE)
C     VECTORS (STORE ADMITTANCE (IMPEDANCE) MATRICES AT X=0 IN ARRAY YO
C     AND THOSE AT X=L IN ARRAY YL. STORE SHORT CIRCUIT CURRENT SOURCE
C     (OPEN CIRCUIT VOLTAGE SOURCE) VECTORS AT X=0 IN ARRAY IO AND
C     THOSE AT X=L IN ARRAY IL.)
C
      IF(OPTION.EQ.11.OR.OPTION.EQ.12) GO TO 34
      WRITE(6,32)
   32 FORMAT(//,18X,'ADMITTANCE AT X=0',10X,'CURRENT SOURCE AT X=0',
     112X,'ADMITTANCE AT X=L',10X,'CURRENT SOURCE AT X=L'/)
      WRITE(6,33)
   33 FORMAT(21X,'(SIEMENS)',23X,'(AMPS)',22X,'(SIEMENS)',23X,'(AMPS)'/)
      GO TO 37
   34 WRITE(6,35)
   35 FORMAT(//,18X,'IMPEDANCE AT X=0',11X,'VOLTAGE SOURCE AT X=0',
     112X,'IMPEDANCE AT X=L',11X,'VOLTAGE SOURCE AT X=L'/)
      WRITE(6,36)
   36 FORMAT(23X,'(OHMS)',23X,'(VOLTS)',24X,'(OHMS)',23X,'(VOLTS)'/)
   37 WRITE(6,38)
   38 FORMAT(' ENTRY',10X,'REAL',11X,'IMAG',11X,'REAL',11X,'IMAG',11X,
     1'REAL',11X,'IMAG',11X,'REAL',11X,'IMAG'//)
      DO 41 I=1,N
      READ(5,39) YOR,YOI,IO(I),YLR,YLI,IL(I)
   39 FORMAT(8(E10.3))
      YO(I,I)=YOR+XJ*YOI
      YL(I,I)=YLR+XJ*YLI
      WRITE(6,40) I,I,YO(I,I),IO(I),YL(I,I),IL(I)
   40 FORMAT(1X,I2,2X,I2,8(5X,1PE10.3)/)
   41 CONTINUE
      IF(OPTION.EQ.11.OR.OPTION.EQ.21) GO TO 45
      IF(N.EQ.1) GO TO 45
      DO 44 I=1,K1
      K2=I+1
      DO 44 J=K2,N
      READ(5,42) YOR,YOI,YLR,YLI
   42 FORMAT(2(E10.3),20X,2(E10.3))
      YO(I,J)=YOR+XJ*YOI
      YL(I,J)=YLR+XJ*YLI
      YO(J,I)=YO(I,J)
      YL(J,I)=YL(I,J)
      WRITE(6,43) I,J,YO(I,J),YL(I,J)
   43 FORMAT(1X,I2,2X,I2,2(5X,1PE10.3),30X,2(5X,1PE10.3))
   44 CONTINUE
C
C     IF THEVENIN EQUIVALENT IS SPECIFIED, SWAP ENTRIES IN M1 AND M2.
C     M1 WILL CONTAIN ZCINV AND M2 WILL CONTAIN ZC.
C
   45 IF(OPTION.EQ.21.OR.OPTION.EQ.22) GO TO 48
      DO 47 I=1,N
      DO 46 J=I,N
      A1=M1(I,J)
      A2=M2(I,J)
      M1(I,J)=A2
      M1(J,I)=A2
      M2(I,J)=A1
   46 M2(J,I)=A1
   47 IL(I)=-IL(I)
C
C     COMPUTE THE MATRIX ZC+ZL*ZCINV*ZO FOR THE THEVENIN EQUIVALENT
C     OR ZCINV+YL*ZC*YO FOR THE NORTON EQUIVALENT. STORE IN ARRAY M2.
C     COMPUTE THE MATRIX ZCINV*ZO FOR THE THEVENIN EQUIVALENT OR
```

```
C     ZC*YO FOR THE NORTON EQUIVALENT. STORE IN ARRAY M1.                 XTALK245
C     COMPUTE THE VECTOR ZL*ZCINV*VO FOR THE THEVENIN EQUIVALENT OR       XTALK246
C     YL*ZC*IO FOR THE NORTON EQUIVALENT. STORE IN ARRAY V2.              XTALK247
C     COMPUTE THE VECTOR ZCINV*VO FOR THE THEVENIN EQUIVALENT OR          XTALK248
C     ZC*IO FOR THE NORTON EQUIVALENT. STORE IN ARRAY V1.                 XTALK249
C                                                                         XTALK250
   48 IF(OPTION.EQ.12.OR.OPTION.EQ.22) GO TO 54                           XTALK251
      DO 50 I=1,N                                                         XTALK252
      SUMO=ZEROC                                                          XTALK253
      DO 49 J=1,N                                                         XTALK254
      A(I,J)=M1(I,J)*YO(J,J)                                              XTALK255
   49 SUMO=SUMO+M1(I,J)*IO(J)                                             XTALK256
   50 V1(I)=SUMO                                                          XTALK257
      DO 52 I=1,N                                                         XTALK258
      DO 51 J=1,N                                                         XTALK259
   51 M2(I,J)=YL(I,I)*A(I,J)+M2(I,J)                                      XTALK260
   52 V2(I)=YL(I,I)*V1(I)                                                 XTALK261
      DO 53 I=1,N                                                         XTALK262
      DO 53 J=1,N                                                         XTALK263
   53 M1(I,J)=A(I,J)                                                      XTALK264
      GO TO 62                                                            XTALK265
   54 DO 57 I=1,N                                                         XTALK266
      SUMO=ZEROC                                                          XTALK267
      DO 56 J=1,N                                                         XTALK268
      SUML=ZEROC                                                          XTALK269
      DO 55 K=1,N                                                         XTALK270
   55 SUML=SUML+M1(I,K)*YO(K,J)                                           XTALK271
      SUMO=SUMO+M1(I,J)*IO(J)                                             XTALK272
   56 A(I,J)=SUML                                                         XTALK273
   57 V1(I)=SUMO                                                          XTALK274
      DO 60 I=1,N                                                         XTALK275
      SUMO=ZEROC                                                          XTALK276
      DO 59 J=1,N                                                         XTALK277
      SUML=ZEROC                                                          XTALK278
      DO 58 K=1,N                                                         XTALK279
   58 SUML=SUML+YL(I,K)*A(K,J)                                            XTALK280
      M2(I,J)=SUML+M2(I,J)                                                XTALK281
   59 SUMO=SUMO+YL(I,J)*V1(J)                                             XTALK282
   60 V2(I)=SUMO                                                          XTALK283
      DO 61 I=1,N                                                         XTALK284
      DO 61 J=1,N                                                         XTALK285
   61 M1(I,J)=A(I,J)                                                      XTALK286
   62 BL=TWO*PI*DSQRT(MUR*ER)*L/V                                         XTALK287
      IF(KER.NE.1) KER=0                                                  XTALK288
      WRITE(6,63) KER                                                     XTALK289
   63 FORMAT(//,' CHARACTERISTIC IMPEDANCE MATRIX INVERSION ERROR= ',I2 XTALK290
     1//)                                                                 XTALK291
C                                                                         XTALK292
C*****FREQUENCY DEPENDENT CALCULATIONS************************************XTALK293
C                                                                         XTALK294
   64 CONTINUE                                                            XTALK295
      READ(5,65,END=82) F                                                 XTALK296
   65 FORMAT(E10.3)                                                       XTALK297
      BETAL=BL*F                                                          XTALK298
      DS=DSIN(BETAL)                                                      XTALK299
      DC=DCOS(BETAL)                                                      XTALK300
C                                                                         XTALK301
C     COMPUTE THE TERMINAL VOLTAGES                                       XTALK302
C                                                                         XTALK303
C     FORM THE EQUATIONS                                                  XTALK304
C                                                                         XTALK305
```

```
      IF(OPTION.EQ.12.OR.OPTION.EQ.22) GO TO 68                          XTALK306
      DO 67 I=1,N                                                        XTALK307
      DO 66 J=1,N                                                        XTALK308
   66 A(I,J)=XJ*DS*M2(I,J)                                               XTALK309
      A(I,I)=DC*(Y0(I,I)+YL(I,I))+A(I,I)                                 XTALK310
   67 B(I)=DC*I0(I)+XJ*DS*V2(I)+IL(I)                                    XTALK311
      GO TO 71                                                           XTALK312
   68 DO 70 I=1,N                                                        XTALK313
      DO 69 J=1,N                                                        XTALK314
   69 A(I,J)=XJ*DS*M2(I,J)+DC*(Y0(I,J)+YL(I,J))                          XTALK315
   70 B(I)=DC*I0(I)+XJ*DS*V2(I)+IL(I)                                    XTALK316
C                                                                        XTALK317
C     SOLVE THE EQUATIONS                                                XTALK318
C                                                                        XTALK319
   71 CALL LEQT1C(A,N,N,B,1,N,0,WA,IER)                                  XTALK320
      IER=IER-128                                                        XTALK321
      IF(IER.NE.1) IER=0                                                 XTALK322
      WRITE(6,72) F,IER                                                  XTALK323
   72 FORMAT(1H1,' FREQUENCY(HERTZ)= ',1PE11.4,10X,'SOLUTION ERROR= ',   XTALK324
     12X,I2///)                                                          XTALK325
      WRITE(6,73)                                                        XTALK326
   73 FORMAT(16X,'WIRE',8X,'VOM(VOLTS)',3X,'VOA(DEGREES)',8X,            XTALK327
     1'VLM(VOLTS)',3X,'VLA(DEGREES)'///)                                 XTALK328
C                                                                        XTALK329
C     COMPUTE AND PRINT THE TERMINAL VOLTAGES                            XTALK330
C                                                                        XTALK331
      DO 75 I=1,N                                                        XTALK332
      SUM0=ZEROC                                                         XTALK333
      DO 74 J=1,N                                                        XTALK334
   74 SUM0=SUM0+M1(I,J)*B(J)                                             XTALK335
   75 WA(I)=XJ*DS*(SUM0-V1(I))+DC*B(I)                                   XTALK336
      DO 81 I=1,N                                                        XTALK337
      IF(OPTION.EQ.11.OR.OPTION.EQ.12) GO TO 76                          XTALK338
      V0=B(I)                                                            XTALK339
      VL=WA(I)                                                           XTALK340
      GO TO 79                                                           XTALK341
   76 IF(OPTION.EQ.12) GO TO 77                                          XTALK342
      V0=I0(I)-Y0(I,I)*B(I)                                              XTALK343
      VL=-IL(I)+YL(I,I)*WA(I)                                            XTALK344
      GO TO 79                                                           XTALK345
   77 SUM0=ZEROC                                                         XTALK346
      SUML=ZEROC                                                         XTALK347
      DO 78 J=1,N                                                        XTALK348
      SUM0=SUM0+Y0(I,J)*B(J)                                             XTALK349
   78 SUML=SUML+YL(I,J)*WA(J)                                            XTALK350
      V0=I0(I)-SUM0                                                      XTALK351
      VL=-IL(I)+SUML                                                     XTALK352
   79 VOM=CDABS(V0)                                                      XTALK353
      VLM=CDABS(VL)                                                      XTALK354
      VOR=DREAL(V0)                                                      XTALK355
      VOI=DIMAG(V0)                                                      XTALK356
      VLR=DREAL(VL)                                                      XTALK357
      VLI=DIMAG(VL)                                                      XTALK358
      IF(VOR.EQ.ZERO.AND.VOI.EQ.ZERO) VOR=ONE                            XTALK359
      IF(VLR.EQ.ZERO.AND.VLI.EQ.ZERO) VLR=ONE                            XTALK360
      VOA=DATAN2(VOI,VOR)*ONE80/PI                                       XTALK361
      VLA=DATAN2(VLI,VLR)*ONE80/PI                                       XTALK362
      WRITE(6,80) I,VOM,VOA,VLM,VLA                                      XTALK363
   80 FORMAT(17X,I2,8X,1PE10.3,3X,1PE10.3,10X,1PE10.3,3X,1PE10.3/)       XTALK364
   81 CONTINUE                                                           XTALK365
      GO TO 64                                                           XTALK366
```

```
82 STOP                                                              XTALK367
   END                                                               XTALK368
```

TABLE A-1

Changes in XTALK to Convert

to Single Precision Arithmetic

Delete Card 054

Card Number		Double		Single
056		REAL *8		REAL
057		COMPLEX *16		COMPLEX
060		3.141592653D0		3.1415926E0
060		2.997925D8		2.997925E8
061-062	change all	D's	to	E's
063		DCMPLX(1.D0,0.D0)		CMPLX(1.E0,0.E0)
064		DCMPLX(0.D0,0.D0)		CMPLX(0.E0,0.E0)
065		DCMPLX(0.D0.1.D0)		CMPLX(0.E0,1.E0)
123		DSQRT		SQRT
134		DLOG		ALOG
136		DLOG		ALOG
138		DLOG		ALOG
145		DREAL		REAL
146		DREAL		REAL
147		DREAL		REAL
148		DREAL		REAL
155		DLOG		ALOG
161		DLOG		ALOG
167		DLOG		ALOG
168		DCOS		COS
168		DCOS		COS

Card Number	Double	Single
287	DSQRT	SQRT
299	DSIN	SIN
300	DCOS	COS
353	CDABS	CABS
354	CDABS	CABS
355	DREAL	REAL
356	DIMAG	AIMAG
357	DREAL	REAL
358	DIMAG	AIMAG
361	DATAN2	ATAN2
362	DATAN2	ATAN2

APPENDIX B

XTALK2

Program Listing

```
C***********************************************************************
C
C            PROGRAM XTALK2
C            (FORTRAN IV, DOUBLE PRECISION)
C            WRITTEN BY
C                 CLAYTON R. PAUL
C                 DEPARTMENT OF ELECTRICAL ENGINEERING
C                 UNIVERSITY OF KENTUCKY
C                 LEXINGTON, KENTUCKY 40506
C
C     A DIGITAL COMPUTER PROGRAM TO COMPUTE THE TERMINAL VOLTAGES
C     (WITH RESPECT TO THE REFERENCE CONDUCTOR) AT THE ENDS OF A
C     MULTICONDUCTOR TRANSMISSION LINE FOR THE TEM MODE OF
C     PROPAGATION.
C
C     THE DISTRIBUTED PARAMETER, MULTICONDUCTOR TRANSMISSION LINE
C     EQUATIONS ARE SOLVED FOR STEADY STATE, SINUSOIDAL EXCITATION
C     OF THE LINE.
C
C     THE LINE CONSISTS OF N WIRES (CYLINDRICAL CONDUCTORS) AND A
C     REFERENCE CONDUCTOR. THE REFERENCE CONDUCTOR MAY BE A WIRE
C     (TYPE=1), AN INFINITE GROUND PLANE (TYPE=2), OR AN OVERALL
C     CYLINDRICAL SHIELD (TYPE=3).
C
C     THE N WIRES ARE ASSUMED TO BE PARALLEL TO EACH OTHER AND THE
C     REFERENCE CONDUCTOR.
C
C     THE N WIRES AND THE REFERENCE CONDUCTOR ARE CONSIDERED TO BE
C     IMPERFECT CONDUCTORS.  THE SELF IMPEDANCES OF EACH WIRE AND THE
C     REFERENCE CONDUCTOR INCLUDE SKIN EFFECT.
C
C     THE LINE IS IMMERSED IN A LINEAR, ISOTROPIC, AND HOMOGENEOUS
C     MEDIUM WITH A RELATIVE PERMEABILITY OF MUR AND A RELATIVE
C     DIELECTRIC CONSTANT OF ER. THE MEDIUM IS ASSUMED TO BE LOSSLESS.
C
C     LOAD STRUCTURE OPTION DEFINITIONS:
C        OPTION=11,THEVENIN EQUIVALENT LOAD STRUCTURES WITH DIAGONAL
C                 IMPEDANCE MATRICES
C        OPTION=12,THEVENIN EQUIVALENT LOAD STRUCTURES WITH FULL
C                 IMPEDANCE MATRICES
C        OPTION=21,NORTON EQUIVALENT LOAD STRUCTURES WITH DIAGONAL
C                 ADMITTANCE MATRICES
C        OPTION=22,NORTON EQUIVALENT LOAD STRUCTURES WITH FULL
C                 ADMITTANCE MATRICES
C
C     SUBROUTINES USED: LEQT1C,EIGCC
C
C***********************************************************************
C
C     ALL VECTORS AND MATRICES IN THE FOLLOWING DIMENSION STATEMENTS
C     SHOULD BE OF SIZE N WHERE N IS THE NUMBER OF WIRES(EXCLUSIVE OF
C     THE REFERENCE CONDUCTOR), I.E., NS(N),C(N,N),Z(N),Y(N),CI(N,N),
C     IO(N),IL(N),YO(N,N),YL(N,N),B(N),A(N,N),P(N,N),EN(N),EP(N),
C     M1(N,N),M2(N,N),V1(N),V2(N),T(N,N),TI(N,N),G(N),V3(N),WA(N)
C     THE VECTOR WK MUST BE OF LENGTH 2N(N+1)
C
      IMPLICIT REAL*8 (A-H,O-Z)
      INTEGER TYPE,OPTION,NS( 2)
      REAL*8 L,LDC,LGP,C( 2, 2),Z( 2),Y( 2),CI( 2, 2),V3( 2),WK( 12),
     1MU02PI,MU04PI,MU08PI,MUR
      COMPLEX*16 XJ,SUMO,SUML,SO,SL,VO,VL,ZO,EPP,ENN,GAM,JOMEGA
```

```
     1,IO( 2),IL( 2),YO( 2, 2),YL( 2, 2),B( 2),A( 2, 2),WA( 2),G( 2),   XTALK062
     2P( 2, 2),EP( 2),EN( 2),M1( 2, 2),M2( 2, 2),V1( 2),V2( 2),         XTALK063
     3T( 2, 2),TI( 2, 2),ZEROC,ONEC                                      XTALK064
      DATA PI/3.141592653D0/,V/2.997925D8/                               XTALK065
      DATA CNTM/2.54D-5/,MUO2PI/2.D-7/,TWO/2.D0/,P5/.5D0/,ONE/1.D0/,     XTALK066
     1FOUR/4.D0/,ONE80/180.D0/,ZERO/0.D0/,MUO8PI/.5D-7/,MUO4PI/1.D-7/,   XTALK067
     2THREE/3.D0/,P25/.25D0/,ONEP15/1.15D0/,P15/.15D0/,P4/.4D0/          XTALK068
      VV=V*V                                                             XTALK069
      ZEROC=DCMPLX(0.D0,0.D0)                                            XTALK070
      ONEC=DCMPLX(1.D0,0.D0)                                             XTALK071
      XJ=DCMPLX(0.D0,1.D0)                                               XTALK072
C                                                                        XTALK073
C*****FREQUENCY INDEPENDENT CALCULATIONS**********************************XTALK074
C                                                                        XTALK075
C     READ AND PRINT INPUT DATA                                          XTALK076
C                                                                        XTALK077
      READ(5,1) TYPE,OPTION,N,ER,MUR,L                                   XTALK078
    1 FORMAT(9X,I1,2(8X,I2),3(5X,E10.3))                                 XTALK079
      IF(TYPE.GE.1.AND.TYPE.LE.3) GO TO 3                                XTALK080
      WRITE(6,2)                                                         XTALK081
    2 FORMAT(' STRUCTURE TYPE ERROR'//' TYPE MUST EQUAL 1,2,OR 3'///)    XTALK082
      GO TO 121                                                          XTALK083
    3 IF(OPTION.EQ.11.OR.OPTION.EQ.12) GO TO 5                           XTALK084
      IF(OPTION.EQ.21.OR.OPTION.EQ.22) GO TO 5                           XTALK085
      WRITE(6,4)                                                         XTALK086
    4 FORMAT(' LOAD STRUCTURE OPTION ERROR'//' OPTION MUST EQUAL 11,12,2XTALK087
     11,OR 22'///)                                                       XTALK088
      GO TO 121                                                          XTALK089
    5 WRITE(6,6) N,TYPE,OPTION,L,ER,MUR                                  XTALK090
    6 FORMAT(1H1,50X,'XTALK2'///                                         XTALK091
     145X,I2,' PARALLEL WIRES'///                                        XTALK092
     243X,' TYPE OF STRUCTURE= ',I1///                                   XTALK093
     341X,' LOAD STRUCTURE OPTION= ',I2///                               XTALK094
     439X,' LINE LENGTH= ',1PE13.6,' METERS'///                          XTALK095
     532X,' DIELECTRIC CONSTANT OF THE MEDIUM= ',1PE10.3///              XTALK096
     631X,' RELATIVE PERMEABILITY OF THE MEDIUM= ',1PE10.3///)           XTALK097
      GO TO (7,15,11),TYPE                                               XTALK098
    7 READ(5,8) RWO                                                      XTALK099
    8 FORMAT(5X,E10.3)                                                   XTALK100
      WRITE(6,9) RWC                                                     XTALK101
    9 FORMAT(' REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A WIRE WITH RADIXTALK102
     1US= ',1PE10.3,' MILS'////)                                         XTALK103
      RWO=RWO*CNTM                                                       XTALK104
      WRITE(6,10)                                                        XTALK105
   10 FORMAT(' WIRE NUMBER',4X,'WIRE RADIUS (MILS)',18X,                 XTALK106
     1'Z COORDINATE (METERS)',24X,'Y COORDINATE (METERS)',//)            XTALK107
      GO TO 18                                                           XTALK108
   11 READ(5,12) RS                                                      XTALK109
   12 FORMAT(5X,E10.3)                                                   XTALK110
      WRITE(6,13) RS                                                     XTALK111
   13 FORMAT(' REFERENCE CONDUCTOR FOR LINE VOLTAGES IS A CYLINDRICAL OVXTALK112
     1ERALL SHIELD WITH INTERIOR RADIUS= ',1PE10.3,' METERS'////)        XTALK113
      RS2=RS*RS                                                          XTALK114
      WRITE(6,14)                                                        XTALK115
   14 FORMAT(' WIRE NUMBER',2X,'WIRE RADIUS (MILS)', 2X,'SEPARATION BETWXTALK116
     1EEN WIRE AND CENTER OF SHIELD (METERS)',6X,'ANGULAR COORDINATE (DEXTALK117
     2GREES)'//)                                                         XTALK118
      GO TO 18                                                           XTALK119
   15 WRITE(6,16)                                                        XTALK120
   16 FORMAT(' REFERENCE CONDUCTOR FOR LINE VOLTAGES IS AN INFINITE GROUXTALK121
     1ND PLANE'////)                                                     XTALK122
```

```
      WRITE(6,17)
   17 FORMAT(' WIRE NUMBER',4X,'WIRE RADIUS (MILS)',18X,
     1'HORIZONTAL COORDINATE (METERS)',16X,'WIRE HEIGHT (METERS)',//)
C
C     READ AND PRINT LINE DIMENSIONS AND COMPUTE THE INVERSE OF THE
C     PER-UNIT-LENGTH CAPACITANCE MATRIX,CINV
C     (STORE CINV IN ARRAY CI)
C
   18 D=MUO2PI*VV/ER
      DO 24 I=1,N
      READ(5,19) RW,Z(I),Y(I)
   19 FORMAT(3(5X,E10.3))
      WRITE(6,20) I,RW,Z(I),Y(I)
   20 FORMAT(2X,I2,13X,1PE10.3,27X,1PE10.3,35X,1PE10.3/)
      RW=RW*CMTM
      GO TO (21,22,23),TYPE
   21 DI2=Z(I)*Z(I)+Y(I)*Y(I)
      CI(I,I)=D*DLOG(DI2/(RW*RWO))
      GO TO 24
   22 CI(I,I)=D*DLOG(TWO*Y(I)/RW)
      GO TO 24
   23 CI(I,I)=D*DLOG((RS2-Z(I)*Z(I))/(RS*RW))
   24 CONTINUE
      IF(N.EQ.1) GO TO 29
      K1=N-1
      DO 28 I=1,K1
      K2=I+1
      DO 28 J=K2,N
      GO TO (25,26,27),TYPE
   25 DI2=Z(I)*Z(I)+Y(I)*Y(I)
      DJ2=Z(J)*Z(J)+Y(J)*Y(J)
      ZD=Z(I)-Z(J)
      YD=Y(I)-Y(J)
      DIJ2=ZD*ZD+YD*YD
      CI(I,J)=P5*D*DLOG(DI2*DJ2/(RWO*RWO*DIJ2))
      CI(J,I)=CI(I,J)
      GO TO 28
   26 ZD=Z(I)-Z(J)
      YD=Y(I)-Y(J)
      DIJ2=ZD*ZD+YD*YD
      CI(I,J)=P5*D*DLOG(ONE+FOUR*Y(I)*Y(J)/DIJ2)
      CI(J,I)=CI(I,J)
      GO TO 28
   27 THETA=(Y(I)-Y(J))*PI/ONE80
      RI2=Z(I)*Z(I)
      RJ2=Z(J)*Z(J)
      CI(I,J)=P5*D*DLOG((RJ2/RS2)*(RI2*RJ2+RS2*RS2-TWO*Z(I)*Z(J)*RS2*
     1DCOS(THETA))/(RI2*RJ2+RJ2*RJ2-TWO*Z(I)*Z(J)*RJ2*DCOS(THETA)))
      CI(J,I)=CI(I,J)
   28 CONTINUE
C
C     COMPUTE THE PER-UNIT-LENGTH CAPACITANCE MATRIX,C
C     (STORE C IN ARRAY C)
C
   29 DO 31 I=1,N
      DO 30 J=1,N
      A(I,J)=CI(I,J)*ONEC
   30 P(I,J)=ZEROC
   31 P(I,I)=ONEC
      CALL LEQT1C(A,N,N,P,N,N,0,WA,KER)
      KER=KER-128
```

```
      IF(KER.NE.1) KER=0
      WRITE(6,32) KER
   32 FORMAT(//,' PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR= ',
     1I2//)
      DO 33 I=1,N
      DO 33 J=1,N
   33 C(I,J)=DREAL(P(I,J))
C
C     READ AND PRINT CHARACTERISTICS OF THE WIRES AND THE REFERENCE
C     CONDUCTOR TO BE USED IN THE SELF IMPEDANCE CALCULATIONS
C
      GO TO (34,40,37),TYPE
   34 READ(5,35) RWSO,SIGO,NSO
   35 FORMAT(2(5X,E10.3),8X,I2)
      WRITE(6,36) RWSO,SIGO,NSO
   36 FORMAT(////' REFERENCE WIRE IS STRANDED WITH EACH STRAND OF RADIUS
     1= ',1PE10.3,' MILS'//' CONDUCTIVITY OF REFERENCE WIRE STRANDS= ',
     21PE10.3,' SIEMENS PER METER'//' NUMBER OF STRANDS= ',I2////)
      RWSO=RWSO*CMTM
      GO TO 43
   37 READ(5,38) TH,SIGO
   38 FORMAT(2(5X,E10.3))
      WRITE(6,39) TH,SIGO
   39 FORMAT(////' SHIELD THICKNESS= ',1PE10.3,' METERS'//' SHIELD CONDU
     1CTIVITY= ',1PE10.3,' SIEMENS PER METER'////)
      GO TO 43
   40 READ(5,41) RGP,LGP
   41 FORMAT(2(5X,E10.3))
      WRITE(6,42) RGP,LGP
   42 FORMAT(////' GROUND PLANE RESISTANCE= ',1PE10.3,' OHMS PER METER'
     1//' GROUND PLANE INDUCTANCE= ',1PE10.3,' HENRYS PER METER'////)
   43 WRITE(6,44)
   44 FORMAT(////' WIRE NUMBER',4X,'WIRE STRAND RADIUS (MILS)',18X,
     1'CONDUCTIVITY (SIEMENS PER METER)',10X,'NUMBER OF STRANDS'//)
      DO 47 I=1,N
      READ(5,45) Z(I),Y(I),NS(I)
   45 FORMAT(2(5X,E10.3),8X,I2)
      WRITE(6,46) I,Z(I),Y(I),NS(I)
   46 FORMAT(2X,I2,16X,1PE10.3,35X,1PE10.3,32X,I2/)
   47 Z(I)=Z(I)*CMTM
C
C     READ AND PRINT ENTRIES IN LOAD ADMITTANCE(IMPEDANCE) MATRICES
C     AND SHORT CIRCUIT CURRENT SOURCE(OPEN CIRCUIT VOLTAGE SOURCE)
C     VECTORS.
C     (STORE ADMITTANCE(IMPEDANCE) MATRICES AT X=0 IN ARRAY YO AND
C     THOSE AT X=L IN ARRAY YL. STORE SHORT CIRCUIT CURRENT SOURCE
C     (OPEN CIRCUIT VOLTAGE SOURCE) VECTORS AT X=0 IN ARRAY IO AND
C     THOSE AT X=L IN ARRAY IL.)
C
      IF(OPTION.EQ.11.OR.OPTION.EQ.12) GO TO 50
      WRITE(6,48)
   48 FORMAT(//,18X,'ADMITTANCE AT X=0',10X,'CURRENT SOURCE AT X=0',
     112X,'ADMITTANCE AT X=L',10X,'CURRENT SOURCE AT X=L'/)
      WRITE(6,49)
   49 FORMAT(21X,'(SIEMENS)',23X,'(AMPS)',22X,'(SIEMENS)',23X,'(AMPS)'/)
      GO TO 53
   50 WRITE(6,51)
   51 FORMAT(//,18X,'IMPEDANCE AT X=0',11X,'VOLTAGE SOURCE AT X=0',
     112X,'IMPEDANCE AT X=L',11X,'VOLTAGE SOURCE AT X=L'/)
      WRITE(6,52)
   52 FORMAT(23X,'(OHMS)',23X,'(VOLTS)',20X,'(OHMS)',23X,'(VOLTS)'/)
```

```
   53 WRITE(6,54)
   54 FORMAT(' ENTRY',10X,'REAL',11X,'IMAG',11X,'REAL',11X,'IMAG',11X,
     1'REAL',11X,'IMAG',11X,'REAL',11X,'IMAG'//)
      DO 57 I=1,N
      READ(5,55) YOR,YOI,IO(I),YLR,YLI,IL(I)
   55 FORMAT(8(E10.3))
      YO(I,I)=YOR+XJ*YOI
      YL(I,I)=YLR+XJ*YLI
      WRITE(6,56) I,I,YO(I,I),IO(I),YL(I,I),IL(I)
   56 FORMAT(1X,I2,2X,I2,8(5X,1PE10.3)/)
   57 CONTINUE
      IF(OPTION.EQ.1..OR.OPTION.EQ.21) GO TO 61
      IF(N.EQ.1) GO TO 61
      DO 60 I=1,K1
      K2=I+1
      DO 60 J=K2,N
      READ(5,58) YOR,YOI,YLR,YLI
   58 FORMAT(2(E10.3),20X,2(E10.3))
      YO(I,J)=YOR+XJ*YOI
      YL(I,J)=YLR+XJ*YLI
      YO(J,I)=YO(I,J)
      YL(J,I)=YL(I,J)
      WRITE(6,59) I,J,YO(I,J),YL(I,J)
   59 FORMAT(1X,I2,2X,I2,2(5X,1PE10.3),30X,2(5X,1PE10.3))
   60 CONTINUE
C
C     COMPUTE THE MATRICES C*ZO,C*ZL,C*VO,C*VL FOR THE THEVENIN
C     EQUIVALENT OR YO*CINV,YL*CINV,IO,IL, FOR THE NORTON EQUIVALENT AND
C     STORE IN ARRAYS M1,M2,V1,V2, RESPECTIVELY.
C
   61 IF(OPTION.EQ.11) GO TO 62
      IF(OPTION.EQ.12) GO TO 65
      IF(OPTION.EQ.21) GO TO 69
      IF(OPTION.EQ.22) GO TO 72
   62 DO 64 I=1,N
      SO=ZEROC
      SL=ZEROC
      DO 63 J=1,N
      M1(I,J)=C(I,J)*YO(J,J)
      M2(I,J)=C(I,J)*YL(J,J)
      SO=SO+C(I,J)*IO(J)
   63 SL=SL+C(I,J)*IL(J)
      V1(I)=SO
   64 V2(I)=SL
      GO TO 76
   65 DO 68 I=1,N
      SO=ZEROC
      SL=ZEROC
      DO 67 J=1,N
      SUMO=ZEROC
      SUML=ZEROC
      DO 66 K=1,N
      SUMO=SUMO+C(I,K)*YO(K,J)
   66 SUML=SUML+C(I,K)*YL(K,J)
      SO=SO+C(I,J)*IO(J)
      SL=SL+C(I,J)*IL(J)
      M1(I,J)=SUMO
   67 M2(I,J)=SUML
      V1(I)=SO
   68 V2(I)=SL
      GO TO 76
```

```
   69 DO 71 I=1,N                                                       XTALK306
      DO 70 J=1,N                                                       XTALK307
      M1(I,J)=Y0(I,I)*CI(I,J)                                           XTALK308
   70 M2(I,J)=YL(I,I)*CI(I,J)                                           XTALK309
      V1(I)=I0(I)                                                       XTALK310
   71 V2(I)=IL(I)                                                       XTALK311
      GO TO 76                                                          XTALK312
   72 DO 75 I=1,N                                                       XTALK313
      DO 74 J=1,N                                                       XTALK314
      SUM0=ZEROC                                                        XTALK315
      SUML=ZEROC                                                        XTALK316
      DO 73 K=1,N                                                       XTALK317
      SUM0=SUM0+Y0(I,K)*CI(K,J)                                         XTALK318
   73 SUML=SUML+YL(I,K)*CI(K,J)                                         XTALK319
      M1(I,J)=SUM0                                                      XTALK320
   74 M2(I,J)=SUML                                                      XTALK321
      V1(I)=I0(I)                                                       XTALK322
   75 V2(I)=IL(I)                                                       XTALK323
   76 CONTINUE                                                          XTALK324
C                                                                       XTALK325
C     SUM THE ENTRIES IN EACH ROW OF C AND STORE IN ARRAY V3            XTALK326
C                                                                       XTALK327
      DO 78 I=1,N                                                       XTALK328
      S=ZERO                                                            XTALK329
      DO 77 J=1,N                                                       XTALK330
   77 S=S+C(I,J)                                                        XTALK331
   78 V3(I)=S                                                           XTALK332
C                                                                       XTALK333
C*****FREQUENCY DEPENDENT CALCULATIONS**********************************XTALK334
C                                                                       XTALK335
   79 CONTINUE                                                          XTALK336
      READ(5,80,END=121) F                                              XTALK337
   80 FORMAT(E10.3)                                                     XTALK338
      OMEGA=TWO*PI*F                                                    XTALK339
      JOMEGA=XJ*OMEGA                                                   XTALK340
C                                                                       XTALK341
C     COMPUTE THE WIRE AND REFERENCE CONDUCTOR SELF IMPEDANCES          XTALK342
C     (STORE SELF IMPEDANCES OF EACH WIRE IN ARRAY B AND THE SELF       XTALK343
C     IMPEDANCE OF THE REFERENCE CONDUCTOR IS STORED IN VARIABLE Z0)    XTALK344
C                                                                       XTALK345
      LDC=MU08PI                                                        XTALK346
      DO 83 I=1,N                                                       XTALK347
      DELTA=ONE/(TWO*PI*DSQRT(Y(I)*F*MU04PI))                           XTALK348
      RDC=ONE/(PI*Y(I)*(Z(I)*Z(I)))                                     XTALK349
      IF(Z(I).LE.DELTA) GO TO 81                                        XTALK350
      IF(Z(I).GE.THREE*DELTA) GO TO 82                                  XTALK351
      B(I)=(P25*(Z(I)/DELTA+THREE)*RDC+JOMEGA*(ONEP15-P15*Z(I)/DELTA)   XTALK352
     1*LDC)/NS(I)                                                       XTALK353
      GO TO 83                                                          XTALK354
   81 B(I)=(RDC+JOMEGA*LDC)/NS(I)                                       XTALK355
      GO TO 83                                                          XTALK356
   82 B(I)=(P5*Z(I)*RDC/DELTA+JOMEGA*TWO*DELTA*LDC/Z(I))/NS(I)          XTALK357
   83 CONTINUE                                                          XTALK358
      GO TO (84,87,88),TYPE                                             XTALK359
   84 DELTA=ONE/(TWO*PI*DSQRT(SIGO*F*MU04PI))                           XTALK360
      RDC=ONE/(PI*SIGO*(RWSO*RWSO))                                     XTALK361
      IF(RWSO.LE.DELTA) GO TO 85                                        XTALK362
      IF(RWSO.GE.THREE*DELTA) GO TO 86                                  XTALK363
      Z0=(P25*(RWSO/DELTA+THREE)*RDC+JOMEGA*(ONEP15-P15*RWSO/DELTA)*LDC)XTALK364
     1/NSO                                                              XTALK365
      GO TO 91                                                          XTALK366
```

```
   85 ZO=(RDC+JOMEGA*LDC)/WSO
      GO TO 91
   86 ZO=(P5*RWSO*RDC/DELTA+JOMEGA*TWO*DELTA*LDC/RWSO)/WSO
      GO TO 91
   87 ZO=(RGP+JOMEGA*LGP)
      GO TO 91
   88 RDC=ONE/(PI*SIGO*TH*(TWO*RS+TH))
      DELTA=ONE/(TWO*PI*DSQRT(SIGO*F*MUO*PI))
      IF(TH.LE.DELTA*P5) GO TO 89
      IF(TH.GE.THREE*DELTA) GO TO 90
      X=TWO*TH/DELTA
      SINH=(DEXP(X)-DEXP(-X))*P5
      COSH=(DEXP(X)+DEXP(-X))*P5
      ZO=((SINH+DSIN(X))+XJ*(SINH-DSIN(X)))/(TWO*PI*RS*SIGO*DELTA*
     1(COSH-DCOS(X)))
      GO TO 91
   89 ZO=(ONE+XJ*P4*TH/DELTA)*RDC
      GO TO 91
   90 ZO=(ONE+XJ)/(TWO*PI*RS*SIGO*DELTA)
C
C     COMPUTE THE EIGENVALUES AND THE EIGENVECTORS OF THE PRODUCT YZ
C     (STORE THE EIGENVECTORS AS COLUMNS OF ARRAY T. STORE THE
C     EIGENVALUES IN ARRAY B.)
C
   91 OM2=OMEGA*OMEGA
      DO 93 I=1,N
      DO 92 J=1,N
   92 A(I,J)=JOMEGA*(V3(I)*ZO+C(I,J)*B(J))
   93 A(I,I)=A(I,I)-OM2*MUR*ER/VV
      CALL EIGCC(A,N,N,2,B,T,N,WK,LER)
      LER=LER-128
      IF(LER.LT.1) LER=0
C
C     COMPUTE THE INVERSE OF THE TRANSFORMATION MATRIX, T
C     (STORE IN ARRAY TI)
C
      DO 95 I=1,N
      DO 94 J=1,N
      A(I,J)=T(I,J)
   94 TI(I,J)=ZEROC
   95 TI(I,I)=ONEC
      CALL LEQT1C(A,N,N,TI,N,N,0,WA,MER)
      MER=MER-128
      IF(MER.NE.1) MER=0
C
C     COMPUTE THE TERMINAL VOLTAGES
C
C     FORM THE EQUATIONS
C
      DO 98 I=1,N
      SO=ZEROC
      SL=ZEROC
      DO 97 J=1,N
      SUMO=ZEROC
      SUML=ZEROC
      DO 96 K=1,N
      SUMO=SUMO+M1(I,K)*T(K,J)
   96 SUML=SUML+M2(I,K)*T(K,J)
      SO=SO+TI(I,J)*V1(J)
      SL=SL+TI(I,J)*V2(J)
      A(I,J)=SUMO
```

```
   97 P(I,J)=SUML
      IO(I)=SO
      IL(I)=SL
      IF(OPTION.EQ.11.OR.OPTION.EQ.12) IL(I)=-IL(I)
      GAM=CDSQRT(B(I))
      EPP=CDEXP(GAM*L)*P5
      ENN=CDEXP(-GAM*L)*P5
      EP(I)=EPP+ENN
      EN(I)=EPP-ENN
      G(I)=GAM/JOMEGA
      IF(OPTION.EQ.11.OR.OPTION.EQ.12) G(I)=CNEC/G(I)
   98 CONTINUE
      DO 100 I=1,N
      DO 100 J=1,N
      SUMO=ZEROC
      SUML=ZEROC
      DO 99 K=1,N
      SUMO=SUMO+TI(I,K)*A(K,J)
   99 SUML=SUML+TI(I,K)*P(K,J)
      YO(I,J)=SUMO
  100 YL(I,J)=SUML
      DO 103 I=1,N
      SO=ZEROC
      DO 102 J=1,N
      SL=ZEROC
      DO 101 K=1,N
  101 SL=SL+YL(I,K)*G(K)*EN(K)*YO(K,J)
      A(I,J)=SL+YL(I,J)*EP(J)+YO(I,J)*EP(I)
  102 SO=SO+YL(I,J)*G(J)*EN(J)*IO(J)
      A(I,I)=A(I,I)+EN(I)/G(I)
  103 B(I)=SO+EP(I)*IO(I)+IL(I)
C
C     SOLVE THE EQUATIONS
C
      CALL LEQT1C(A,N,N,B,1,N,0,WA,IER)
      IER=IER-128
      IF(IER.NE.1) IER=0
      WRITE(6,104) F,IER
  104 FORMAT(1H1,' FREQUENCY(HERTZ)= ',1PE11.4,10X,'SOLUTION ERROR= ',
     12X,I2/)
      PREC=WK(1)
      WRITE(6,105) LER,PREC
  105 FORMAT(' EIGEN SOLUTION ERROR= ',I4/' EIGEN SOLUTION PRECISION= ',
     11PE10.3/)
      WRITE(6,106) MER
  106 FORMAT(' TRANSFORMATION MATRIX INVERSION ERROR= ',I2//)
      WRITE(6,107)
  107 FORMAT(16X,'WIRE',8X,'VOM(VOLTS)',3X,'VOA(DEGREES)',8X,
     1'VLM(VOLTS)',3X,'VLA(DEGREES)'///)
C
C     COMPUTE AND PRINT THE TERMINAL VOLTAGES
C
      DO 109 I=1,N
      SO=ZEROC
      DO 108 J=1,N
  108 SO=SO+YO(I,J)*B(J)
  109 G(I)=-G(I)*EN(I)*IO(I)+EP(I)*B(I)+G(I)*EN(I)*SO
      IF(OPTION.EQ.21.OR.OPTION.EQ.22) GO TO 114
      DO 111 I=1,N
      SO=ZEROC
      SL=ZEROC
```

```
      DO 110 J=1,N                                                      XTALK489
      SO=SO-YO(I,J)*B(J)                                                XTALK490
  110 SL=SL+YL(I,J)*G(J)                                                XTALK491
      YO(I,I)=IO(I)+SO                                                  XTALK492
  111 YL(I,I)=-IL(I)+SL                                                 XTALK493
      DO 113 I=1,N                                                      XTALK494
      SO=ZEROC                                                          XTALK495
      SL=ZEROC                                                          XTALK496
      DO 112 J=1,N                                                      XTALK497
      SO=SO+T(I,J)*YO(J,J)                                              XTALK498
  112 SL=SL+T(I,J)*YL(J,J)                                              XTALK499
      P(I,I)=SO                                                         XTALK500
  113 A(I,I)=SL                                                         XTALK501
      GO TO 117                                                         XTALK502
  114 DO 116 I=1,N                                                      XTALK503
      SO=ZEROC                                                          XTALK504
      SL=ZEROC                                                          XTALK505
      DO 115 J=1,N                                                      XTALK506
      SO=SO+T(I,J)*B(J)                                                 XTALK507
  115 SL=SL+T(I,J)*G(J)                                                 XTALK508
      P(I,I)=SO                                                         XTALK509
  116 A(I,I)=SL                                                         XTALK510
  117 DO 120 I=1,N                                                      XTALK511
      SO=ZEROC                                                          XTALK512
      SL=ZEROC                                                          XTALK513
      DO 118 J=1,N                                                      XTALK514
      SO=SO+CI(I,J)*P(J,J)                                              XTALK515
  118 SL=SL+CI(I,J)*A(J,J)                                              XTALK516
      VO=SO                                                             XTALK517
      VL=SL                                                             XTALK518
      VOM=CDABS(VO)                                                     XTALK519
      VLM=CDABS(VL)                                                     XTALK520
      VOR=DREAL(VO)                                                     XTALK521
      VOI=DIMAG(VO)                                                     XTALK522
      VLR=DREAL(VL)                                                     XTALK523
      VLI=DIMAG(VL)                                                     XTALK524
      IF(VOR.EQ.ZERO.AND.VOI.EQ.ZERO) VOR=ONE                           XTALK525
      IF(VLR.EQ.ZERO.AND.VLI.EQ.ZERO) VLR=ONE                           XTALK526
      VOA=DATAN2(VOI,VOR)*ONE80/PI                                      XTALK527
      VLA=DATAN2(VLI,VLR)*ONE80/PI                                      XTALK528
      WRITE(6,119)  I,VOM,VOA,VLM,VLA                                   XTALK529
  119 FORMAT(17X,I2,8X,1PE10.3,3X,1PE10.3,10X,1PE10.3,3X,1PE10.3/)     XTALK530
  120 CONTINUE                                                          XTALK531
      GO TO 79                                                          XTALK532
  121 STOP                                                              XTALK533
      END                                                               XTALK534
```

TABLE B-1

Changes in XTALK2 to Convert

to Single Precision Arithmetic

Delete Card 057

Card Number		Double		Single
059		REAL *8		REAL
061		COMPLEX *16		COMPLEX
065		3.141592653DC		3.1415926E0
065		2.997925D8		2.997925E8
066-068	change all	D's	to	E's
070		DCMPLX(0.D0,0.D0)		CMPLX(0.E0,0.E0)
071		DCMPLX(1.D0,0.D0)		CMPLX(1.E0,0.E0)
072		DCMPLX(0.D0,1.D0)		CMPLX(0.E0,1.E0)
140		DLOG		ALOG
142		DLOG		ALOG
144		DLOG		ALOG
157		DLOG		ALOG
163		DLOG		ALOG
169		DLOG		ALOG
170		DCOS		COS
170		DCOS		COS
190		DREAL		REAL
348		DSQRT		SQRT
360		DSQRT		SQRT
374		DSQRT		SQRT
378		DEXP		EXP
378		DEXP		EXP

Card Number	Double	Single
379	DEXP	EXP
379	DEXP	EXP
380	DSIN	SIN
380	DSIN	SIN
381	DCOS	COS
432	CDSQRT	CSQRT
433	CDEXP	CEXP
434	CDEXP	CEXP
519	CDABS	CABS
520	CDABS	CABS
521	DREAL	REAL
522	DIMAG	AIMAG
523	DREAL	REAL
524	DIMAG	AIMAG
527	DATAN2	ATAN2
528	DATAN2	ATAN2

APPENDIX C

FLATPAK

Program Listing

```
C************************************************************************
C
C           PROGRAM FLATPAK
C           (FORTRAN IV, DOUBLE PRECISION)
C           WRITTEN BY
C                CLAYTON R. PAUL
C                DEPARTMENT OF ELECTRICAL ENGINEERING
C                UNIVERSITY OF KENTUCKY
C                LEXINGTON, KENTUCKY 40506
C
C     A DIGITAL COMPUTER PROGRAM TO COMPUTE THE TERMINAL VOLTAGES
C     (WITH RESPECT TO THE REFERENCE WIRE) OF AN N+1 WIRE FLATPACK OR
C     RIBBON CABLE FOR THE 'QUASI-TEM' MODE OF PROPAGATION.
C
C     THE DISTRIBUTED PARAMETER, MULTICONDUCTOR TRANSMISSION LINE
C     EQUATIONS ARE SOLVED FOR STEADY STATE, SINUSOIDAL EXCITATION
C     OF THE LINE.
C
C     THE N+1 WIRES ARE ASSUMED TO BE PARALLEL TO EACH OTHER.
C
C     THE N+1 WIRES ARE CONSIDERED TO BE PERFECT CONDUCTORS.
C
C     THE SURROUNDING MEDIA ARE ASSUMED TO BE LOSSLESS.
C
C     THE PER-UNIT-LENGTH CAPACITANCES OF THE CABLE(WITH AND WITHOUT
C     THE DIELECTRIC INSULATIONS PRESENT) ARE INPUT DATA AND MAY BE
C     COMPUTED WITH THE PROGRAM GETCAP.
C
C     LOAD STRUCTURE OPTION DEFINITIONS:
C        OPTION=11,THEVENIN EQUIVALENT LOAD STRUCTURES WITH DIAGONAL
C                  IMPEDANCE MATRICES
C        OPTION=12,THEVENIN EQUIVALENT LOAD STRUCTURES WITH FULL
C                  IMPEDANCE MATRICES
C        OPTION=21,NORTON EQUIVALENT LOAD STRUCTURES WITH DIAGONAL
C                  ADMITTANCE MATRICES
C        OPTION=22,NORTON EQUIVALENT LOAD STRUCTURES WITH FULL
C                  ADMITTANCE MATRICES
C
C     SUBROUTINES USED: LEQT1C,NROOT,EIGEN
C
C************************************************************************
C
C     ALL VECTORS AND MATRICES IN THE FOLLOWING DIMENSION STATEMENTS
C     SHOULD BE OF SIZE N WHERE N IS THE NUMBER OF WIRES(EXCLUSIVE OF
C     THE REFERENCE WIRE), I.E., C(N,N),CO(N,N),TI(N,N),G(N),WA(N),
C     IO(N),IL(N),YO(N,N),YL(N,N),B(N),A(N,N),P(N,N)
C
      IMPLICIT REAL*8 (A-H,O-Z)
      INTEGER OPTION
      REAL*8 L,C( 2, 2),CO( 2, 2),TI( 2, 2),G( 2)
      COMPLEX*16 XJ,SUMO,SUML,SO,SL,VO,VL,ZEROC,ONEC,IO( 2),IL( 2),
     1YO( 2, 2),YL( 2, 2),B( 2),A( 2, 2),WA( 2),P( 2, 2)
      DATA PI/3.141592653D0/,V/2.997925D8/
      DATA ONE/1.D0/,TWO/2.D0/,ZERO/0.D0/,ONE80/180.D0/
      ZEROC=DCMPLX(0.D0,0.D0)
      ONEC=DCMPLX(1.D0,0.D0)
      XJ=DCMPLX(0.D0,1.D0)
C
C*****FREQUENCY INDEPENDENT CALCULATIONS*********************************
C
C     READ AND PRINT INPUT DATA
```

```
C
      READ(5,1) N,OPTION,L
    1 FORMAT(8X,I2,8X,I2,E10.3)
      IF(OPTION.EQ.11.OR.OPTION.EQ.12) GO TO 3
      IF(OPTION.EQ.21.OR.OPTION.EQ.22) GO TO 3
      WRITE(6,2)
    2 FORMAT(' LOAD STRUCTURE OPTION ERROR'//' OPTION MUST EQUAL 11,12,2
     11,OR 22'///)
      GO TO 60
    3 NP=N+1
      WRITE(6,4) NP,L,OPTION
    4 FORMAT(1H1,49X,'FLATPAK'///
     145X,I2,' PARALLEL WIRES'///
     239X,'LINE LENGTH= ',1PE13.6,' METERS'///
     342X,'LOAD STRUCTURE OPTION= ',I2///)
C
C     READ ENTRIES IN THE PER-UNIT-LENGTH TRANSMISSION LINE
C     CAPACITANCE MATRIX,C(COMPUTED WITH GETCAP)
C     (STORE C IN ARRAY C)
C
      DO 6 I=1,N
      DO 6 J=I,N
      READ(5,5) K,M,C(K,M)
    5 FORMAT(4X,I2,3X,I2,2X,E13.6)
    6 C(M,K)=C(K,M)
C
C     READ ENTRIES IN THE PER-UNIT-LENGTH TRANSMISSION LINE
C     CAPACITANCE MATRIX WITH THE WIRE INSULATIONS REMOVED, CO,(COMPUTED
C     WITH GETCAP)
C     (STORE CO IN ARRAY CO)
C
      DO 8 I=1,N
      DO 8 J=I,N
      READ(5,7) K,M,CO(K,M)
    7 FORMAT(4X,I2,3X,I2,2X,E13.6)
    8 CO(M,K)=CO(K,M)
C
C     COMPUTE THE EIGENVECTORS (COLUMNS OF THE MATRIX T) AND EIGENVALUES
C     OF THE MATRIX PRODUCT CL
C     (THE ARRAYS TI AND G CONTAIN T AND THE INVERSE OF THE EIGENVALUES
C     FOR THE THEVENIN EQUIVALENT OR THE INVERSE OF THE TRANSPOSE OF T
C     AND THE EIGENVALUES FOR THE NORTON EQUIVALENT, RESPECTIVELY)
C
      IF(N.EQ.1) GO TO 9
      CALL NROOT(N,CO,C,G,TI,N*N)
      GO TO 10
    9 G(1)=CO(1,1)/C(1,1)
      TI(1,1)=ONE/DSQRT(C(1,1))
   10 DO 12 I=1,N
      DO 11 J=1,N
   11 C(I,J)=TI(I,J)
   12 G(I)=ONE/(V*DSQRT(G(I)))
      IF(OPTION.EQ.21.OR.OPTION.EQ.22) GO TO 18
      DO 14 I=1,N
      DO 13 J=1,N
      A(I,J)=TI(I,J)*ONEC
   13 P(I,J)=ZEROC
   14 P(I,I)=ONEC
      CALL LEQT1C(A,N,N,P,N,N,0,WA,KER)
      KER=KER-128
      IF(KER.NE.1) KER=0
```

```
      WRITE(6,15) KER                                                   FLATP123
   15 FORMAT(//,' TRANSFORMATION MATRIX INVERSION ERROR= ',I2//)        FLATP124
      DO 17 I=1,N                                                       FLATP125
      DO 16 J=1,N                                                       FLATP126
   16 TI(I,J)=DREAL(P(J,I))                                             FLATP127
   17 G(I)=ONE/G(I)                                                     FLATP128
C                                                                       FLATP129
C     READ AND PRINT ENTRIES IN LOAD ADMITTANCE(IMPEDANCE) MATRICES     FLATP130
C     AND SHORT CIRCUIT CURRENT SOURCE(OPEN CIRCUIT VOLTAGE SOURCE)     FLATP131
C     VECTORS                                                           FLATP132
C     (STORE ADMITTANCE(IMPEDANCE) MATRICES AT X=0 IN ARRAY YO AND THOSEFLATP133
C     AT X=L IN ARRAY YL. STORE SHORT CIRCUIT CURRENT SOURCE(OPEN       FLATP134
C     CIRCUIT VOLTAGE SOURCE) VECTORS AT X=0 IN ARRAY IO AND THOSE      FLATP135
C     AT X=L IN ARRAY IL.)                                              FLATP136
C                                                                       FLATP137
   18 IF(OPTION.EQ.11.OR.OPTION.EQ.12) GO TO 21                         FLATP138
      WRITE(6,19)                                                       FLATP139
   19 FORMAT(//,18X,'ADMITTANCE AT X=0',10X,'CURRENT SOURCE AT X=0',    FLATP140
     112X,'ADMITTANCE AT X=L',10X,'CURRENT SOURCE AT X=L'/)             FLATP141
      WRITE(6,20)                                                       FLATP142
   20 FORMAT(21X,'(SIEMENS)',23X,'(AMPS)',22X,'(SIEMENS)',23X,'(AMPS)'/)FLATP143
      GO TO 24                                                          FLATP144
   21 WRITE(6,22)                                                       FLATP145
   22 FORMAT(//,18X,'IMPEDANCE AT X=0',11X,'VOLTAGE SOURCE AT X=0',     FLATP146
     112X,'IMPEDANCE AT X=L',11X,'VOLTAGE SOURCE AT X=L'/)              FLATP147
      WRITE(6,23)                                                       FLATP148
   23 FORMAT(23X,'(OHMS)',23X,'(VOLTS)',24X,'(OHMS)',23X,'(VOLTS)'/)    FLATP149
   24 WRITE(6,25)                                                       FLATP150
   25 FORMAT(' ENTRY',10X,'REAL',11X,'IMAG',11X,'REAL',11X,'IMAG',11X,  FLATP151
     1'REAL',11X,'IMAG',11X,'REAL',11X,'IMAG'//)                        FLATP152
      DO 28 I=1,N                                                       FLATP153
      READ(5,26) YOR,YOI,IO(I),YLR,YLI,IL(I)                            FLATP154
   26 FORMAT(8(E10.3))                                                  FLATP155
      YO(I,I)=YOR+XJ*YOI                                                FLATP156
      YL(I,I)=YLR+XJ*YLI                                                FLATP157
      WRITE(6,27) I,I,YO(I,I),IO(I),YL(I,I),IL(I)                       FLATP158
   27 FORMAT(1X,I2,2X,I2,8(5X,1PE10.3)/)                                FLATP159
   28 CONTINUE                                                          FLATP160
      IF(OPTION.EQ.11.OR.OPTION.EQ.21) GO TO 32                         FLATP161
      IF (N.EQ.1) GO TO 32                                              FLATP162
      K1=N-1                                                            FLATP163
      DO 31 I=1,K1                                                      FLATP164
      K2=I+1                                                            FLATP165
      DO 31 J=K2,N                                                      FLATP166
      READ(5,29) YOR,YOI,YLR,YLI                                        FLATP167
   29 FORMAT(2(E10.3),20X,2(E10.3))                                     FLATP168
      YO(I,J)=YOR+XJ*YOI                                                FLATP169
      YL(I,J)=YLR+XJ*YLI                                                FLATP170
      YO(J,I)=YO(I,J)                                                   FLATP171
      YL(J,I)=YL(I,J)                                                   FLATP172
      WRITE(6,30) I,J,YO(I,J),YL(I,J)                                   FLATP173
   30 FORMAT(1X,I2,2X,I2,2(5X,1PE10.3),30X,2(5X,1PE10.3))               FLATP174
   31 CONTINUE                                                          FLATP175
C                                                                       FLATP176
C     COMPUTE THE MATRICES TTRAN*ZO*T, TTRAN*ZL*T, TTRAN*VO, -TTRAN*VL  FLATP177
C     FOR THE THEVENIN EQUIVALENT OR TINV*YO*TINVTRAN, TINV*YL*TINVTRAN,FLATP178
C     TINV*IO, TINV*IL FOR THE NORTON EQUIVALENT AND STORE IN ARRAYS    FLATP179
C     YO,YL,IO,IL, RESPECTIVELY.                                        FLATP180
C                                                                       FLATP181
   32 IF(OPTION.EQ.12.OR.OPTION.EQ.22) GO TO 35                         FLATP182
      DO 34 I=1,N                                                       FLATP183
```

```
      S0=ZEROC
      SL=ZEROC
      DO 33 J=1,N
      A(I,J)=Y0(I,I)*TI(I,J)
      P(I,J)=YL(I,I)*TI(I,J)
      S0=S0+TI(J,I)*I0(J)
   33 SL=SL+TI(J,I)*IL(J)
      B(I)=S0
   34 WA(I)=SL
      GO TO 39
   35 DO 38 I=1,N
      S0=ZEROC
      SL=ZEROC
      DO 37 J=1,N
      SUM0=ZEROC
      SUML=ZEROC
      DO 36 K=1,N
      SUM0=SUM0+Y0(I,K)*TI(K,J)
   36 SUML=SUML+YL(I,K)*TI(K,J)
      A(I,J)=SUM0
      P(I,J)=SUML
      S0=S0+TI(J,I)*I0(J)
   37 SL=SL+TI(J,I)*IL(J)
      B(I)=S0
   38 WA(I)=SL
   39 DO 42 I=1,N
      DO 41 J=1,N
      S0=ZEROC
      SL=ZEROC
      DO 40 K=1,N
      S0=S0+TI(K,I)*A(K,J)
   40 SL=SL+TI(K,I)*P(K,J)
      Y0(I,J)=S0
   41 YL(I,J)=SL
      I0(I)=B(I)
      IL(I)=WA(I)
   42 IF(OPTION.EQ.11.OR.OPTION.EQ.12) IL(I)=-IL(I)
C
C*****FREQUENCY DEPENDENT CALCULATIONS***********************************
C
   43 CONTINUE
      READ(5,44,END=60) F
   44 FORMAT(E10.3)
      OMEGA=TWO*PI*F
C
C     COMPUTE THE TERMINAL VOLTAGES
C
C     FORM THE EQUATIONS
C
      DO 45 I=1,N
      W=G(I)
      IF(OPTION.EQ.11.OR.OPTION.EQ.12) W=ONE/W
      W=OMEGA*W*L
      CO(I,I)=DCOS(W)
   45 P(I,I)=XJ*DSIN(W)
      DO 48 I=1,N
      S0=ZEROC
      DO 47 J=1,N
      SL=ZEROC
      DO 46 K=1,N
   46 SL=SL+YL(I,K)*G(K)*P(K,K)*Y0(K,J)
```

```
      A(I,J)=SL+YL(I,J)*CO(J,J)+YO(I,J)*CO(I,I)
   47 SO=SO+YL(I,J)*G(J)*P(J,J)*IO(J)
      A(I,I)=A(I,I)+P(I,I)/G(I)
   48 B(I)=SO+CO(I,I)*IO(I)+IL(I)
C
C     SOLVE THE EQUATIONS
C
      CALL LEQT1C(A,N,N,B,1,N,0,WA,IER)
      IER=IER-128
      IF(IER.NE.1) IER=0
      WRITE(6,49) F,IER
   49 FORMAT(1H1,' FREQUENCY(HERTZ)= ',1PE11.4,10X,'SOLUTION ERROR= ',
     12X,I2/)
      WRITE(6,50)
   50 FORMAT(16X,'WIRE',8X,'VOM(VOLTS)',3X,'VOA(DEGREES)',8X,
     1'VLM(VOLTS)',3X,'VLA(DEGREES)'///)
C
C     COMPUTE AND PRINT THE TERMINAL VOLTAGES
C
      DO 52 I=1,N
      SO=ZEROC
      DO 51 J=1,N
   51 SO=SO+YO(I,J)*B(J)
   52 WA(I)=-G(I)*P(I,I)*IO(I)+CO(I,I)*B(I)+G(I)*P(I,I)*SO
      IF(OPTION.EQ.21.OR.OPTION.EQ.22) GO TO 56
      DO 54 I=1,N
      SO=ZEROC
      SL=ZEROC
      DO 53 J=1,N
      SO=SO-YO(I,J)*B(J)
   53 SL=SL+YL(I,J)*WA(J)
      A(I,I)=IO(I)+SO
   54 P(I,I)=-IL(I)+SL
      DO 55 I=1,N
      B(I)=A(I,I)
   55 WA(I)=P(I,I)
   56 DO 59 I=1,N
      SO=ZEROC
      SL=ZEROC
      DO 57 J=1,N
      SO=SO+C(I,J)*B(J)
   57 SL=SL+C(I,J)*WA(J)
      VO=SO
      VL=SL
      VOM=CDABS(VO)
      VLM=CDABS(VL)
      VOR=DREAL(VO)
      VOI=DIMAG(VO)
      VLR=DREAL(VL)
      VLI=DIMAG(VL)
      IF(VOR.EQ.ZERO.AND.VOI.EQ.ZERO) VOR=ONE
      IF(VLR.EQ.ZERO.AND.VLI.EQ.ZERO) VLR=ONE
      VOA=DATAN2(VOI,VOR)*ONE80/PI
      VLA=DATAN2(VLI,VLR)*ONE80/PI
      WRITE(6,58) I,VOM,VOA,VLM,VLA
   58 FORMAT(17X,I2,8X,1PE10.3,3X,1PE10.3,10X,1PE10.3,3X,1PE10.3/)
   59 CONTINUE
      GO TO 43
   60 STOP
      END
```

TABLE C-1

Changes in FLATPAK to Convert

to Single Precision Arithmetic

Delete Card 048

Card Number		Double		Single
050		REAL *8		REAL
051		COMPLEX *16		COMPLEX
053		3.141592653D0		3.1415926E0
053		2.997925D8		2.997925E8
054	change all	D's	to	E's
055		DCMPLX(0.D0,0.D0)		CMPLX(0.E0,0.E0)
056		DCMPLX(1.D0,0.D0)		CMPLX(1.E0,0.E0)
057		DCMPLX(0.D0,1.D0)		CMPLX(0.E0,1.E0)
109		DSQRT		SQRT
113		DSQRT		SQRT
127		DREAL		REAL
237		DCOS		COS
238		DSIN		SIN
289		CDABS		CABS
290		CDABS		CABS
291		DREAL		REAL
292		DIMAG		AIMAG
293		DREAL		REAL
294		DIMAG		AIMAG
297		DATAN2		ATAN2
298		DATAN2		ATAN2

APPENDIX D

FLATPAK2

Program Listing

```
C**********************************************************************
C
C             PROGRAM FLATPAK2
C             (FORTRAN IV, DOUBLE PRECISION)
C             WRITTEN BY
C                  CLAYTON R. PAUL
C                  DEPARTMENT OF ELECTRICAL ENGINEERING
C                  UNIVERSITY OF KENTUCKY
C                  LEXINGTON, KENTUCKY 40506
C
C     A DIGITAL COMPUTER PROGRAM TO COMPUTE THE TERMINAL VOLTAGES
C     (WITH RESPECT TO THE REFERENCE WIRE) OF AN N+1 WIRE FLATPACK OR
C     RIBBON CABLE FOR THE 'QUASI-TEM' MODE OF PROPAGATION.
C
C     THE DISTRIBUTED PARAMETER, MULTICONDUCTOR TRANSMISSION LINE
C     EQUATIONS ARE SOLVED FOR STEADY STATE, SINUSOIDAL EXCITATION
C     OF THE LINE.
C
C     THE N+1 WIRES ARE ASSUMED TO BE PARALLEL TO EACH OTHER.
C
C     THE N+1 WIRES ARE CONSIDERED TO BE IMPERFECT CONDUCTORS. THE SELF
C     IMPEDANCES OF EACH WIRE INCLUDE SKIN EFFECT.
C
C     THE SURROUNDING MEDIA ARE ASSUMED TO BE LOSSLESS.
C
C     THE PER-UNIT-LENGTH CAPACITANCES OF THE CABLE(WITH AND WITHOUT
C     THE DIELECTRIC INSULATIONS PRESENT) ARE INPUT DATA AND MAY BE
C     COMPUTED WITH THE PROGRAM GETCAP.
C
C     LOAD STRUCTURE OPTION DEFINITIONS:
C        OPTION=11,THEVENIN EQUIVALENT LOAD STRUCTURES WITH DIAGONAL
C                  IMPEDANCE MATRICES
C        OPTION=12,THEVENIN EQUIVALENT LOAD STRUCTURES WITH FULL
C                  IMPEDANCE MATRICES
C        OPTION=21,NORTON EQUIVALENT LOAD STRUCTURES WITH DIAGONAL
C                  ADMITTANCE MATRICES
C        OPTION=22,NORTON EQUIVALENT LOAD STRUCTURES WITH FULL
C                  ADMITTANCE MATRICES
C
C     SUBROUTINES USED: LEQT1C,EIGCC
C
C**********************************************************************
C
C     ALL VECTORS AND MATRICES IN THE FOLLOWING DIMENSION STATEMENTS
C     SHOULD BE OF SIZE N WHERE N IS THE NUMBER OF WIRES(EXCLUSIVE OF
C     THE REFERENCE WIRE), I.E., C(N,N),CO(N,N),CI(N,N)
C     IO(N),IL(N),YO(N,N),YL(N,N),B(N),A(N,N),P(N,N),EN(N),EP(N),
C     M1(N,N),M2(N,N),V1(N),V2(N),T(N,N),TI(N,N),G(N),V3(N),WA(N)
C     THE VECTOR WK MUST BE OF LENGTH 2N(N+1)
C
      IMPLICIT REAL*8 (A-H,O-Z)
      INTEGER OPTION
      REAL*8 L,LDC,C( 2, 2),CO( 2, 2),V3( 2),CI( 2, 2),WK( 12),
     1MUO4PI,MUO8PI
      COMPLEX*16 XJ,SUMO,SUML,SO,SL,VO,VL,ZEROC,ONEC,Z,EPP,ENN,GAM
     1,IO( 2),IL( 2),YO( 2, 2),YL( 2, 2),B( 2),A( 2, 2),WA( 2),G( 2),
     2P( 2, 2),EP( 2),EN( 2),M1( 2, 2),M2( 2, 2),V1( 2),V2( 2),
     3T( 2, 2),TI( 2, 2),JOMEGA
      DATA PI/3.141592653D0/,V/2.997925D8/
      DATA CMTM/2.54D-5/,ZERO/0.D0/,TWO/2.D0/,MUO8PI/.5D-7/,ONE/1.D0/,
     1MUO4PI/1.D-7/,THREE/3.D0/,P25/.25D0/,ONEP15/1.15D0/,P15/.15D0/,
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```
     2P5/.5D0/,ONE80/180.D0/                                           FLATP062
      VV=V*V                                                           FLATP063
      ZEROC=DCMPLX(0.D0,0.D0)                                          FLATP064
      ONEC=DCMPLX(1.D0,0.D0)                                           FLATP065
      XJ=DCMPLX(0.D0,1.D0)                                             FLATP066
C                                                                      FLATP067
C*****FREQUENCY INDEPENDENT CALCULATIONS********************************FLATP068
C                                                                      FLATP069
C     READ AND PRINT INPUT DATA                                        FLATP070
C                                                                      FLATP071
      READ(5,1) N,OPTION,L                                             FLATP072
    1 FORMAT(8X,I2,8X,I2,E10.3)                                        FLATP073
      IF(OPTION.EQ.11.OR.OPTION.EQ.12) GO TO 3                         FLATP074
      IF(OPTION.EQ.21.OR.OPTION.EQ.22) GO TO 3                         FLATP075
      WRITE(6,2)                                                       FLATP076
    2 FORMAT(' LOAD STRUCTURE OPTION ERROR'//' OPTION MUST EQUAL 11,12,2FLATP077
     11,OR 22'///)                                                     FLATP078
      GO TO 81                                                         FLATP079
    3 NP=N+1                                                           FLATP080
      WRITE(6,4) NP,L,OPTION                                           FLATP081
    4 FORMAT(1H1,49X,'FLATPAK2'///                                     FLATP082
     145X,I2,' PARALLEL WIRES'///                                      FLATP083
     239X,'LINE LENGTH= ',1PE13.6,' METERS'///                         FLATP084
     342X,'LOAD STRUCTURE OPTION= ',I2///)                             FLATP085
C                                                                      FLATP086
C     READ ENTRIES IN THE PER-UNIT-LENGTH TRANSMISSION LINE            FLATP087
C     CAPACITANCE MATRIX,C (COMPUTED WITH GETCAP)                      FLATP088
C     (STORE C IN ARRAY C)                                             FLATP089
C                                                                      FLATP090
      DO 6 I=1,N                                                       FLATP091
      DO 6 J=I,N                                                       FLATP092
      READ(5,5) K,M,C(K,M)                                             FLATP093
    5 FORMAT(4X,I2,3X,I2,2X,E13.6)                                     FLATP094
    6 C(M,K)=C(K,M)                                                    FLATP095
C                                                                      FLATP096
C     READ ENTRIES IN THE PER-UNIT-LENGTH TRANSMISSION LINE            FLATP097
C     CAPACITANCE MATRIX WITH THE WIRE INSULATIONS REMOVED,CO (COMPUTED FLATP098
C     WITH GETCAP)                                                     FLATP099
C     (STORE CO IN ARRAY CO)                                           FLATP100
C                                                                      FLATP101
      DO 8 I=1,N                                                       FLATP102
      DO 8 J=I,N                                                       FLATP103
      READ(5,7) K,M,CO(K,M)                                            FLATP104
    7 FORMAT(4X,I2,3X,I2,2X,E13.6)                                     FLATP105
    8 CO(M,K)=CO(K,M)                                                  FLATP106
C                                                                      FLATP107
C     COMPUTE THE PER-UNIT-LENGTH TRANSMISSION LINE INDUCTANCE MATRIX,L,FLATP108
C     AND THE INVERSE OF THE CAPACITANCE MATRIX,CI                     FLATP109
C     (STORE CI IN ARRAY CI AND L IN ARRAY CO)                         FLATP110
C                                                                      FLATP111
      DO 10 I=1,N                                                      FLATP112
      DO 9 J=1,N                                                       FLATP113
      T(I,J)=C(I,J)*ONEC                                               FLATP114
      A(I,J)=CO(I,J)*ONEC                                              FLATP115
      TI(I,J)=ZEROC                                                    FLATP116
    9 P(I,J)=ZEROC                                                     FLATP117
      TI(I,I)=ONEC                                                     FLATP118
   10 P(I,I)=ONEC                                                      FLATP119
      CALL LEQT1C(A,N,N,P,N,N,0,WA,KER)                                FLATP120
      CALL LEQT1C(T,N,N,TI,N,N,0,WA,NER)                               FLATP121
      KER=KER-128                                                      FLATP122
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```
      NER=NER-128                                                       FLATP123
      IF(KER.NE.1) KER=0                                                FLATP124
      IF(NER.NE.1) NER=0                                                FLATP125
      WRITE(6,11) KER                                                   FLATP126
      WRITE(6,11) NER                                                   FLATP127
   11 FORMAT(//,' PER-UNIT-LENGTH CAPACITANCE MATRIX INVERSION ERROR= ',FLATP128
     1I2//)                                                             FLATP129
      DO 12 I=1,N                                                       FLATP130
      DO 12 J=1,N                                                       FLATP131
      CI(I,J)=DREAL(TI(I,J))                                            FLATP132
   12 CO(I,J)=DREAL(P(I,J))/VV                                          FLATP133
C                                                                       FLATP134
C     READ AND PRINT CHARACTERISTICS OF THE WIRES TO BE USED IN THE SELFFLATP135
C     IMPEDANCE CALCULATIONS                                            FLATP136
C                                                                       FLATP137
      READ(5,13) RWS,SIG,NS                                             FLATP138
   13 FORMAT(2(5X,E10.3),8X,I2)                                         FLATP139
      WRITE(6,14) RWS,SIG,NS                                            FLATP140
   14 FORMAT(////' WIRES ARE STRANDED WITH EACH STRAND OF RADIUS= ',    FLATP141
     11PE10.3,' MILS'//' CONDUCTIVITY OF WIRE STRANDS= ',               FLATP142
     21PE10.3,' SIEMENS PER METER'//' NUMBER OF STRANDS= ',I2////)      FLATP143
      RWS=RWS*CMTM                                                      FLATP144
C                                                                       FLATP145
C     READ AND PRINT ENTRIES IN LOAD ADMITTANCE(IMPEDANCE) MATRICES     FLATP146
C     AND SHORT CIRCUIT CURRENT SOURCE(OPEN CIRCUIT VOLTAGE SOURCE)     FLATP147
C     VECTORS                                                           FLATP148
C     (STORE ADMITTANCE(IMPEDANCE) MATRICES AT X=0 IN ARRAY YO AND      FLATP149
C     THOSE AT X=L IN ARRAY YL. STORE SHORT CIRCUIT CURRENT SOURCE      FLATP150
C     (OPEN CIRCUIT VOLTAGE SOURCE) VECTORS AT X=0 IN ARRAY IO AND      FLATP151
C     THOSE AT X=L IN ARRAY IL.)                                        FLATP152
C                                                                       FLATP153
      IF(OPTION.EQ.11.OR.OPTION.EQ.12) GO TO 17                         FLATP154
      WRITE(6,15)                                                       FLATP155
   15 FORMAT(//,18X,'ADMITTANCE AT X=0',10X,'CURRENT SOURCE AT X=0',    FLATP156
     112X,'ADMITTANCE AT X=L',10X,'CURRENT SOURCE AT X=L'/)             FLATP157
      WRITE(6,16)                                                       FLATP158
   16 FORMAT(21X,'(SIEMENS)',23X,'(AMPS)',22X,'(SIEMENS)',23X,'(AMPS)'/)FLATP159
      GO TO 20                                                          FLATP160
   17 WRITE(6,18)                                                       FLATP161
   18 FORMAT(//,18X,'IMPEDANCE AT X=0',11X,'VOLTAGE SOURCE AT X=0',     FLATP162
     112X,'IMPEDANCE AT X=L',11X,'VOLTAGE SOURCE AT X=L'/)              FLATP163
      WRITE(6,19)                                                       FLATP164
   19 FORMAT(23X,'(OHMS)',23X,'(VOLTS)',24X,'(OHMS)',23X,'(VOLTS)'/)    FLATP165
   20 WRITE(6,21)                                                       FLATP166
   21 FORMAT(' ENTRY',10X,'REAL',11X,'IMAG',11X,'REAL',11X,'IMAG',11X,  FLATP167
     1'REAL',11X,'IMAG',11X,'REAL',11X,'IMAG'//)                        FLATP168
      DO 24 I=1,N                                                       FLATP169
      READ(5,22) YOR,YOI,IO(I),YLR,YLI,IL(I)                            FLATP170
   22 FORMAT(8(E10.3))                                                  FLATP171
      YO(I,I)=YOR+XJ*YOI                                                FLATP172
      YL(I,I)=YLR+XJ*YLI                                                FLATP173
      WRITE(6,23) I,I,YO(I,I),IO(I),YL(I,I),IL(I)                       FLATP174
   23 FORMAT(1X,I2,2X,I2,8(5X,1PE10.3)/)                                FLATP175
   24 CONTINUE                                                          FLATP176
      IF(OPTION.EQ.11.OR.OPTION.EQ.21) GO TO 28                         FLATP177
      IF(N.EQ.1) GO TO 28                                               FLATP178
      K1=N-1                                                            FLATP179
      DO 27 I=1,K1                                                      FLATP180
      K2=I+1                                                            FLATP181
      DO 27 J=K2,N                                                      FLATP182
      READ(5,25) YOR,YOI,YLR,YLI                                        FLATP183
```

```
   25 FORMAT(2(E10.3),20X,2(E10.3))
      Y0(I,J)=Y0R+XJ*Y0I
      YL(I,J)=YLR+XJ*YLI
      Y0(J,I)=Y0(I,J)
      YL(J,I)=YL(I,J)
      WRITE(6,26) I,J,Y0(I,J),YL(I,J)
   26 FORMAT(1X,I2,2X,I2,2(5X,1PE10.3),30X,2(5X,1PE10.3))
   27 CONTINUE
C
C     COMPUTE AND STORE THE MATRICES AND VECTORS C*Z0, C*ZL, C*V0, C*VL
C     FOR THE THEVENIN EQUIVALENT OR Y0*CINV, YL*CINV, I0, IL FOR THE
C     NORTON EQUIVALENT IN ARRAYS M1,M2,V1,V2, RESPECTIVELY
C
   28 IF(OPTION.EQ.11) GO TO 29
      IF(OPTION.EQ.12) GO TO 32
      IF(OPTION.EQ.21) GO TO 36
      IF(OPTION.EQ.22) GO TO 39
   29 DO 31 I=1,N
      S0=ZEROC
      SL=ZEROC
      DO 30 J=1,N
      M1(I,J)=C(I,J)*Y0(J,J)
      M2(I,J)=C(I,J)*YL(J,J)
      S0=S0+C(I,J)*I0(J)
   30 SL=SL+C(I,J)*IL(J)
      V1(I)=S0
   31 V2(I)=SL
      GO TO 43
   32 DO 35 I=1,N
      S0=ZEROC
      SL=ZEROC
      DO 34 J=1,N
      SUM0=ZEROC
      SUML=ZEROC
      DO 33 K=1,N
      SUM0=SUM0+C(I,K)*Y0(K,J)
   33 SUML=SUML+C(I,K)*YL(K,J)
      S0=S0+C(I,J)*I0(J)
      SL=SL+C(I,J)*IL(J)
      M1(I,J)=SUM0
   34 M2(I,J)=SUML
      V1(I)=S0
   35 V2(I)=SL
      GO TO 43
   36 DO 38 I=1,N
      DO 37 J=1,N
      M1(I,J)=Y0(I,I)*CI(I,J)
   37 M2(I,J)=YL(I,I)*CI(I,J)
      V1(I)=I0(I)
   38 V2(I)=IL(I)
      GO TO 43
   39 DO 42 I=1,N
      DO 41 J=1,N
      SUM0=ZEROC
      SUML=ZEROC
      DO 40 K=1,N
      SUM0=SUM0+Y0(I,K)*CI(K,J)
   40 SUML=SUML+YL(I,K)*CI(K,J)
      M1(I,J)=SUM0
   41 M2(I,J)=SUML
      V1(I)=I0(I)
```

```
   42 V2(I)=IL(I)
   43 CONTINUE
C
C     COMPUTE THE MATRIX C*L AND STORE IN ARRAY CO. COMPUTE THE SUMS
C     OF ELEMENTS IN EACH ROW OF C AND STORE IN ARRAY V3.
C
      DO 46 I=1,N
      S=ZERO
      DO 45 J=1,N
      SS=ZERO
      DO 44 K=1,N
   44 SS=SS+C(I,K)*CO(K,J)
      P(I,J)=SS*ONEC
   45 S=S+C(I,J)
   46 V3(I)=S
      DO 47 I=1,N
      DO 47 J=1,N
   47 CO(I,J)=DREAL(P(I,J))
C
C*****FREQUENCY DEPENDENT CALCULATIONS************************************
C
   48 CONTINUE
      READ(5,49,END=81) F
   49 FORMAT(E10.3)
      OMEGA=TWO*PI*F
      JOMEGA=XJ*OMEGA
C
C     COMPUTE THE WIRE SELF IMPEDANCES
C
      LDC=MU08PI
      DELTA=ONE/(TWO*PI*DSQRT(SIG*F*MU04PI))
      RDC=ONE/(PI*SIG*RWS*RWS)
      IF(RWS.LE.DELTA) GO TO 50
      IF(RWS.GE.THREE*DELTA) GO TO 51
      Z=(P25*(RWS/DELTA+THREE)*RDC+JOMEGA*(ONEP15-P15*RWS/DELTA)*LDC)/NS
      GO TO 52
   50 Z=(RDC+JOMEGA*LDC)/NS
      GO TO 52
   51 Z=(P5*RWS*RDC/DELTA+JOMEGA*TWO*DELTA*LDC/RWS)/NS
C
C     COMPUTE THE EIGENVALUES AND THE EIGENVECTORS OF THE PRODUCT YZ
C     (STORE THE EIGENVECTORS AS COLUMNS OF ARRAY T AND THE EIGENVALUES
C     IN ARRAY B)
C
   52 OM2=OMEGA*OMEGA
      DO 53 I=1,N
      DO 53 J=1,N
   53 A(I,J)=JOMEGA*Z*(V3(I)+C(I,J))-OM2*CO(I,J)
      CALL EIGCC(A,N,N,2,B,T,N,WK,LER)
      LER=LER-128
      IF(LER.LT.1) LER=0
C
C     COMPUTE THE INVERSE OF THE TRANSFORMATION MATRIX, T
C     (STORE THE INVERSE IN ARRAY TI)
C
      DO 55 I=1,N
      DO 54 J=1,N
      A(I,J)=T(I,J)
   54 TI(I,J)=ZEROC
   55 TI(I,I)=ONEC
      CALL LEQT1C(A,N,N,TI,N,N,0,WA,NER)
```

```
      NER=NER-128
      IF(NER.NE.1) NER=0
C
C     COMPUTE THE TERMINAL VOLTAGES
C
C     FORM THE EQUATIONS
C
      DO 58 I=1,N
      S0=ZEROC
      SL=ZEROC
      DO 57 J=1,N
      SUM0=ZEROC
      SUML=ZEROC
      DO 56 K=1,N
      SUM0=SUM0+M1(I,K)*T(K,J)
   56 SUML=SUML+M2(I,K)*T(K,J)
      S0=S0+TI(I,J)*V1(J)
      SL=SL+TI(I,J)*V2(J)
      A(I,J)=SUM0
   57 P(I,J)=SUML
      I0(I)=S0
      IL(I)=SL
      IF(OPTION.EQ.11.OR.OPTION.EQ.12) IL(I)=-IL(I)
      GAM=CDSQRT(B(I))
      EPP=CDEXP(GAM*L)*P5
      ENN=CDEXP(-GAM*L)*P5
      EP(I)=EPP+ENN
      EN(I)=EPP-ENN
      G(I)=GAM/JOMEGA
      IF(OPTION.EQ.11.OR.OPTION.EQ.12) G(I)=ONEC/G(I)
   58 CONTINUE
      DO 60 I=1,N
      DO 60 J=1,N
      SUM0=ZEROC
      SUML=ZEROC
      DO 59 K=1,N
      SUM0=SUM0+TI(I,K)*A(K,J)
   59 SUML=SUML+TI(I,K)*P(K,J)
      Y0(I,J)=SUM0
   60 YL(I,J)=SUML
      DO 63 I=1,N
      S0=ZEROC
      DO 62 J=1,N
      SL=ZEROC
      DO 61 K=1,N
   61 SL=SL+YL(I,K)*G(K)*EN(K)*Y0(K,J)
      A(I,J)=SL+YL(I,J)*EP(J)+Y0(I,J)*EP(I)
   62 S0=S0+YL(I,J)*G(J)*EN(J)*I0(J)
      A(I,I)=A(I,I)+EN(I)/G(I)
   63 B(I)=S0+EP(I)*I0(I)+IL(I)
C
C     SOLVE THE EQUATIONS
C
      CALL LEQT1C(A,N,N,B,1,N,0,WA,IER)
      IER=IER-128
      IF(IER.NE.1) IER=0
      WRITE(6,64) F,IER
   64 FORMAT(1H1,' FREQUENCY(HERTZ)= ',1PE11.4,10X,'SOLUTION ERROR= ',
     12X,I2/)
      WRITE(6,65) IER,WK(1)
   65 FORMAT(' EIGEN SOLUTION ERROR= ',I4/' EIGEN SOLUTION PRECISION= ',
```

```
     11PE10.3/)
      WRITE(6,66) NER
   66 FORMAT(' TRANSFORMATION MATRIX INVERSION ERROR= ',I2//)
      WRITE(6,67)
   67 FORMAT(16X,'WIRE',8X,'VOM(VOLTS)',3X,'VOA(DEGREES)',8X,
     1'VLM(VOLTS)',3X,'VLA(DEGREES)'///)
C
C     COMPUTE AND PRINT THE TERMINAL VOLTAGES
C
      DO 69 I=1,N
      S0=ZEROC
      DO 68 J=1,N
   68 S0=S0+Y0(I,J)*B(J)
   69 G(I)=-G(I)*EN(I)*I0(I)-EP(I)*B(I)+G(I)*EN(I)*S0
      IF(OPTION.EQ.21.OR.OPTION.EQ.22) GO TO 74
      DO 71 I=1,N
      S0=ZEROC
      SL=ZEROC
      DO 70 J=1,N
      S0=S0-Y0(I,J)*B(J)
   70 SL=SL+YL(I,J)*G(J)
      Y0(I,I)=I0(I)+S0
   71 YL(I,I)=-IL(I)+SL
      DO 73 I=1,N
      S0=ZEROC
      SL=ZEROC
      DO 72 J=1,N
      S0=S0+T(I,J)*Y0(J,J)
   72 SL=SL+T(I,J)*YL(J,J)
      P(I,I)=S0
   73 A(I,I)=SL
      GO TO 77
   74 DO 76 I=1,N
      S0=ZEROC
      SL=ZEROC
      DO 75 J=1,N
      S0=S0+T(I,J)*B(J)
   75 SL=SL+T(I,J)*G(J)
      P(I,I)=S0
   76 A(I,I)=SL
   77 DO 80 I=1,N
      S0=ZEROC
      SL=ZEROC
      DO 78 J=1,N
      S0=S0+CI(I,J)*P(J,J)
   78 SL=SL+CI(I,J)*A(J,J)
      V0=S0
      VL=SL
      VOM=CDABS(V0)
      VLM=CDABS(VL)
      VOR=DREAL(V0)
      VOI=DIMAG(V0)
      VLR=DREAL(VL)
      VLI=DIMAG(VL)
      IF(VOR.EQ.ZERO.AND.VOI.EQ.ZERO) VOR=ONE
      IF(VLR.EQ.ZERO.AND.VLI.EQ.ZERO) VLR=ONE
      VOA=DATAN2(VOI,VOR)*ONE80/PI
      VLA=DATAN2(VLI,VLR)*ONE80/PI
      WRITE(6,79) I,VOM,VOA,VLM,VLA
   79 FORMAT(17X,I2,8X,1PE10.3,3X,1PE10.3,10X,1PE10.3,3X,1PE10.3/)
   80 CONTINUE
```

```
      GO TO 48                                                          FLATP428
   81 STOP                                                              FLATP429
      END                                                               FLATP430
```

TABLE D-1

Changes in FLATPAK2 to Convert

to Single Precision Arithmetic

Delete Card 051

Card Number		Double		Single
053		REAL *8		REAL
055		COMPLEX *16		COMPLEX
059		3.141592653D0		3.1415926E0
059		2.997925D8		2.997925E8
060-062	change all	D's	to	E's
064		DCMPLX(0.D0,0.D0)		CMPLX(0.E0,0.E0)
065		DCMPLX(1.D0,0.D0)		CMPLX(1.E0,0.E0)
066		DCMPLX(0.D0,1.D0)		CMPLX(0.E0,1.E0)
132		DREAL		REAL
133		DREAL		REAL
262		DREAL		REAL
275		DSQRT		SQRT
329		CDSQRT		CSQRT
330		CDEXP		CEXP
331		CDEXP		CEXP
415		CDABS		CABS
416		CDABS		CABS
417		DREAL		REAL
418		DIMAG		AIMAG
419		DREAL		REAL
420		DIMAG		AIMAG

Card Number	Double	Single
423	DATAN2	ATAN2
424	DATAN2	ATAN2

APPENDIX E

NROOT

Subroutine Listing

```
      SUBROUTINE NROOT(M,A,B,XL,X,MA)
      REAL*8 A(MA),B(MA),XL(M),X(MA),SUMV,ZERO,ONE
      DATA ZERO/0.D0/,ONE/1.D0/
      K=1
      DO 1 J=2,M
      L=M*(J-1)
      DO 1 I=1,J
      L=L+1
      K=K+1
    1 B(K)=B(L)
      MV=0
      CALL EIGEN(B,X,M,MV,M*M)
      L=0
      DO 2 J=1,M
      L=L+J
    2 XL(J)=ONE/DSQRT(DABS(B(L)))
      K=0
      DO 3 J=1,M
      DO 3 I=1,M
      K=K+1
    3 B(K)=X(K)*XL(J)
      DO 4 I=1,M
      N2=0
      DO 4 J=1,M
      N1=M*(I-1)
      L=M*(J-1)+I
      X(L)=ZERO
      DO 4 K=1,M
      N1=N1+1
      N2=N2+1
    4 X(L)=X(L)+B(N1)*A(N2)
      L=0
      DO 5 J=1,M
      DO 5 I=1,J
      N1=I-M
      N2=M*(J-1)
      L=L+1
      A(L)=ZERO
      DO 5 K=1,M
      N1=N1+M
      N2=N2+1
    5 A(L)=A(L)+X(N1)*B(N2)
      CALL EIGEN (A,X,M,MV,M*M)
      L=0
      DO 6 I=1,M
      L=L+I
    6 XL(I)=A(L)
      DO 7 I=1,M
      N2=0
      DO 7 J=1,M
      N1=I-M
      L=M*(J-1)+I
      A(L)=ZERO
      DO 7 K=1,M
      N1=N1+M
      N2=N2+1
    7 A(L)=A(L)+B(N1)*X(N2)
      K=0
      DO 8 J=1,M
      DO 8 I=1,M
      K=K+1
```

```
    8 X(K)=A(K)                                                         NROOT062
      RETURN                                                            NROOT063
      END                                                               NROOT064
```

TABLE E-1

Changes in NROOT to Convert to Single Precision Arithmetic

Card Number		Double		Single
002		REAL *8		REAL
003	change all	D's	to	E's
016		DSQRT		SQRT
016		DABS		ABS

APPENDIX F

EIGEN

Subroutine Listing

```
      SUBROUTINE EIGEN(A,R,N,MV,MA)
      REAL*8 A(MA),R(MA),ANORM,ANRMX,THR,X,Y,SINX,SINX2,COSX,COSX2,
     1SINCS,RANGE,ZERO,ONE,P5,TWO
      DATA ZERO/0.D0/,ONE/1.D0/,P5/.5D0/,TWO/2.D0/
    1 RANGE=1.0D-12
      IF(MV-1) 2,5,2
    2 IQ=-N
      DO 4 J=1,N
      IQ=IQ+N
      DO 4 I=1,N
      IJ=IQ+I
      R(IJ)=ZERO
      IF(I-J) 4,3,4
    3 R(IJ)=ONE
    4 CONTINUE
    5 ANORM=ZERO
      DO 7 I=1,N
      DO 7 J=I,N
      IF(I-J) 6,7,6
    6 IA=I+(J*J-J)/2
      ANORM=ANORM+A(IA)*A(IA)
    7 CONTINUE
      IF(ANORM) 36,36,8
    8 ANORM=DSQRT(TWO)*DSQRT(ANORM)
      ANRMX=ANORM*RANGE/FLOAT(N)
      IND=0
      THR=ANORM
    9 THR=THR/FLOAT(N)
   10 L=1
   11 M=L+1
   12 MQ=(M*M-M)/2
      LQ=(L*L-L)/2
      LM=L+MQ
   13 IF(DABS(A(LM))-THR) 29,14,14
   14 IND=1
      LL=L+LQ
      MM=M+MQ
      X=P5*(A(LL)-A(MM))
   15 Y=-A(LM)/DSQRT(A(LM)*A(LM)+X*X)
      IF(X) 16,17,17
   16 Y=-Y
   17 SINX=Y/DSQRT(TWO*(ONE+(DSQRT(ONE-Y*Y))))
      SINX2=SINX*SINX
   18 COSX=DSQRT(ONE-SINX2)
      COSX2=COSX*COSX
      SINCS =SINX*COSX
      ILQ=N*(L-1)
      IMQ=N*(M-1)
      DO 28 I=1,N
      IQ=(I*I-I)/2
      IF(I-L) 19,26,19
   19 IF(I-M) 20,26,21
   20 IM=I+MQ
      GO TO 22
   21 IM=M+IQ
   22 IF(I-L) 23,24,24
   23 IL=I+LQ
      GO TO 25
   24 IL=L+IQ
   25 X=A(IL)*COSX-A(IM)*SINX
      A(IM)=A(IL)*SINX+A(IM)*COSX
```

```
      A(IL)=X                                                  EIGEN062
   26 IF(MV-1) 27,28,27                                        EIGEN063
   27 ILR=ILQ+I                                                EIGEN064
      IMR=IMQ+I                                                EIGEN065
      X=R(ILR)*COSX-R(IMR)*SINX                                EIGEN066
      R(IMR)=R(ILR)*SINX+R(IMR)*COSX                           EIGEN067
      R(ILR)=X                                                 EIGEN068
   28 CONTINUE                                                 EIGEN069
      X=TWO*A(LM)*SINCS                                        EIGEN070
      Y=A(LL)*COSX2+A(MM)*SINX2-X                              EIGEN071
      X=A(LL)*SINX2+A(MM)*COSX2+X                              EIGEN072
      A(LM)=(A(LL)-A(MM))*SINCS+A(LM)*(COSX2-SINX2)            EIGEN073
      A(LL)=Y                                                  EIGEN074
      A(MM)=X                                                  EIGEN075
   29 IF(M-N) 30,31,30                                         EIGEN076
   30 M=M+1                                                    EIGEN077
      GO TO 12                                                 EIGEN078
   31 IF(L-(N-1)) 32,33,32                                     EIGEN079
   32 L=L+1                                                    EIGEN080
      GO TO 11                                                 EIGEN081
   33 IF(IND-1) 35,34,35                                       EIGEN082
   34 IND=0                                                    EIGEN083
      GO TO 10                                                 EIGEN084
   35 IF(THR-ANRMX) 36,36,9                                    EIGEN085
   36 IQ=-N                                                    EIGEN086
      DO 40 I=1,N                                              EIGEN087
      IQ=IQ+N                                                  EIGEN088
      LL=I+(I*I-I)/2                                           EIGEN089
      JQ=N*(I-2)                                               EIGEN090
      DO 40 J=I,N                                              EIGEN091
      JQ=JQ+N                                                  EIGEN092
      MM=J+(J*J-J)/2                                           EIGEN093
      IF(A(LL)-A(MM)) 37,40,40                                 EIGEN094
   37 X=A(LL)                                                  EIGEN095
      A(LL)=A(MM)                                              EIGEN096
      A(MM)=X                                                  EIGEN097
      IF(MV-1) 38,40,38                                        EIGEN098
   38 DO 39 K=1,N                                              EIGEN099
      ILR=IQ+K                                                 EIGEN100
      IMR=JQ+K                                                 EIGEN101
      X=R(ILR)                                                 EIGEN102
      R(ILR)=R(IMR)                                            EIGEN103
   39 R(IMR)=X                                                 EIGEN104
   40 CONTINUE                                                 EIGEN105
      RETURN                                                   EIGEN106
      END                                                      EIGEN107
```

TABLE F-1

Changes in EIGEN to Convert

to Single Precision Arithmetic

Card Number		Double		Single
002		REAL *8		REAL
004	change all	D's	to	E's
005		1.0D-12		1.0E-6
024		DSQRT		SQRT
024		DSQRT		SQRT
034		DABS		ABS
039		DSQRT		SQRT
042		DSQRT		SQRT
042		DSQRT		SQRT
044		DSQRT		SQRT